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EXPERIMENTAL WORKSHOP ON
HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED MATERIALS
(ADVANCED ACTIVITIES)

(26 November - 14 December 1990)

" Critical currents and their physical problems in high T_c oxide superconductors "

presented by:

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Critical currents and their physical problems in high T_c oxide superconductors

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REFERENCES

Introduction

A.M. Campbell and J.E. Evetts, Adv. Phys. 21, 199 (1972

A.I. Larkin and Yu.N. Ovchinnikov, J. Low Temp. Phys. 34, 409 (1979)

E.H. Brandt and U. Essmann, Phys. Stat. Sol. B 144, 13 (1987)

J.W. Ekin, K. Salama, V. Selvamanickam, preprint

C.P. Bean, Phys. Rev. Lett. 8, 250 (1962)

C.P. Bean, Phys. Rev. Lett. 36, 31 (1964)

R.W. Rollins, H. Küpfer and W. Gey, J. Appl. Phys. 45, 5392 (1974)

Granularity

J.R. Clem, Physica C 153-155, 50-55 (1988)

G. Deutscher and K.A. Müller, Phys. Rev. Lett. 59, 1745 (1987)

H. Küpfer, I. Apfelstedt, R. Flükiger, C. Keller, R. Meier-Hirmer, B. Runtsch, A. Turowski, U. Wiech and T. Wolf, Cryogenics 28, 650 (1988)

T. Wolf, W. Goldacker, B. Obst, G. Roth and R. Flükiger, J. Crystal Growth 96, 1010 (1989)

H. Küpfer, C. Keller, T. Wolf, I. Apfelstedt, R. Meier-Hirmer, U. Wiech and R. Flükiger, Progr. High Temp. Superconductivity 18, 172 (1989)

M. Däumling, J. Seuntjens and D.C. Larbalestier, Nature 346, 332 (1990)

K. Salama, V. Selvamanickam, L. Gao and K. Sun, Appl. Phys. Lett. 54, 2352 (1989)

C.M. Gyorgy, R.B. van Dover, K.A. Jackson, L.F. Schneemeyer and J.V. Waszczak, Appl. Phys. Lett. 55, 283 (1989)

C. Keller, H. Küpfer, R. Meier-Hirmer, U. Wiech, V. Selvamanickam and K. Salama, Cryogenics 30, 401 (1990)

M. Murakami, S. Gotoh, N. Koshizuka, T. Tanaka, T. Matsushita, S. Kambe and K. Kitazawa, Cryogenics 30, 390 (1990)

Relaxation

P.W. Anderson and Y.B. Kim, Rev. Mod. Phys. 36, 39 (1964)

M.R. Beasley, R. Labusch and W.W. Webb, Phys. Rev. 181, 682 (1969)

D. Dew-Hughes, Cryogenics 28, 674 (1988)

C.W. Hagen, R.P. Griessen and E. Salomons, Physica C 157, 199 (1989)

C. Keller, H. Küpfer, R. Meier-Hirmer, U. Wiech, V. Selvamanickam and K. Salama, Cryogenics 30, 410 (1990)

V.V. Moshchalkov, A.A. Gippius, A.A. Zhukov, H.H. Nyan, V.I. Voronkova and V.K. Yanovskii, Physica C 165, 62 (1990)

T. Fujiyoshi, K. Toko, T. Matsushita and K. Yamafuji, Jpn. J. Appl. Phys. 28, L 1906 (1989)

Y. Xu, M. Suenaga, A.R. Moodenbaugh, D.O. Welch, Phys. Rev. B40, 10882-10890 (1989)

M.P. Maley et. al., Phys. Rev. B42, 2639-2642 (1990)

D.O. Welch, to be published in IEEE Trans. on Magnetics (1990)

J.Z. Sun, C.B. Eom, B. Lairson, J.C. Bravman and T.H. Geballe, to be published in Phys. Rev. Lett. (1990)

C.W. Hagen and R.P. Griessen, Phys. Rev. Lett. 62, 2857 (1989)

A. Gurevich, H. Küpfer and C. Keller, to be published

high field high current application :

$10^5\,A/cm^2$ ($B \lesssim 10T$, $77K$) $\rho < 10^{-7}\,\mu\Omega\,cm$

Introduction

critical currents in Typ II supercond.

measurement techniques of j_c

1). granularity

detection of weak supercond. coupling

in a ceramic (intergrain)

in a single crystal (intragrain)

2). Low pinning energy

problems of flux pinning

investigation in High T_c s.c.

3). thermal relaxation

time dependent decay of j_c

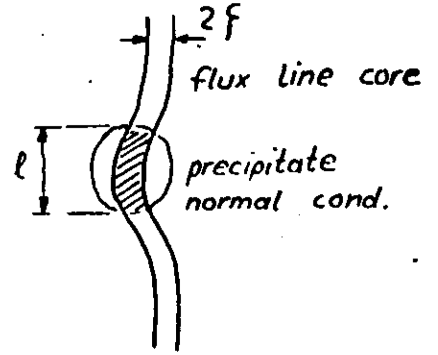
B and T dependence of activation energy

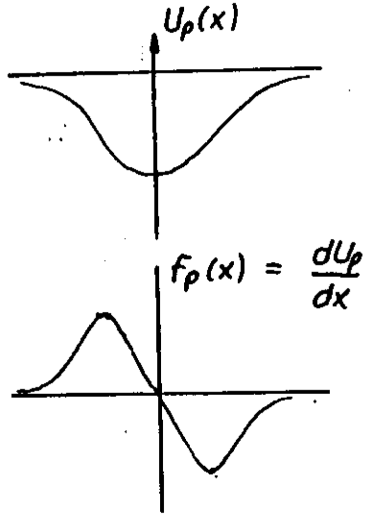
4). reversible region between B_{irr} and B_{c2}

measurement of B_{c2} and B_{irr}

correlation between defect structure and $B_{i..}$

Pinning potential $U_p \approx \frac{1}{2}\mu_0 H_c^2 \pi \xi^2 \ell$





elementary pinning force f_p

f_p^{max} $10^{-10} \div 10^{-15}$ N

summation of f_p

- interaction energy between flux lines $U_{ij} \ll U_p$

  $F_p = N f_p$

  direct summation ("strong pins")

  N : defect density

- $U_{ij} > U_p$

  $F_p = \sqrt{\frac{N f_p^2}{V}} \sim N^2 f_p^4$

  collective pinning ("weak pins")

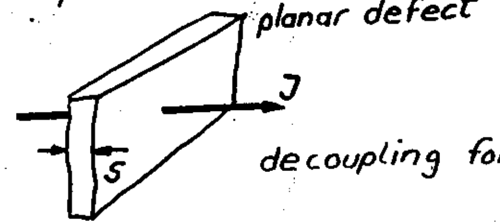
  V : correlation volume

Larkin and Ovchinnikov

	low T_c	high T_c
ξ	50 Å	5 Å
operation temp.	4 K	77 K

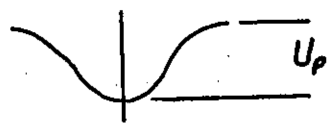
defect dimension similar

1) granularity



decoupling for $s > \xi$

2) low pinning energy



$U_p \sim \xi^n$ $n \geq 1$

3) thermal activation

$U_0(U_p)/k_B T$ (77 K) $\lesssim$ 10

$U_0(U_p)/k_B T$ (4 K) $\gtrsim$ 100

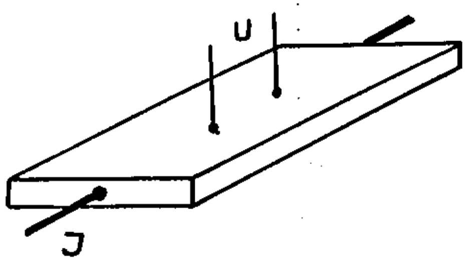
4) reversible region between B_{irr} and B_{c2}

$U_0(U_p)/k_B T$ $(B_{irr}) \approx 1$

$j_c = 0$ at $B_{irr} < B < B_{c2}$

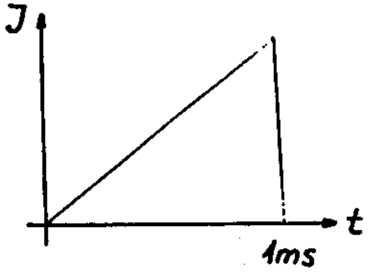
measurement techniques for j_c

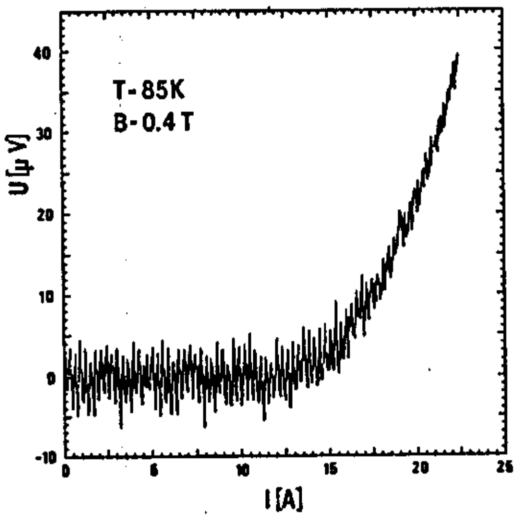
1) resistive dc : transport j_c



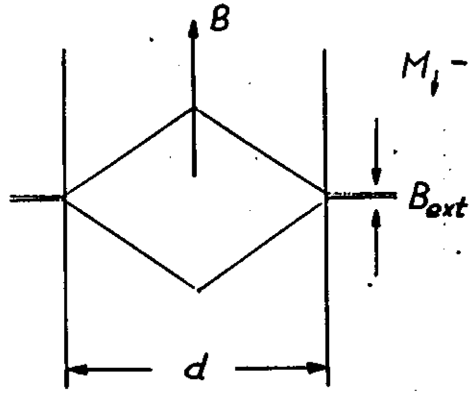
- $E \geq 0.1\ \mu V/cm$
  short sample length
- bath cooled (4 K or 77 K)
  high contact resistance J. Ekin

bulk specimen : current pulse





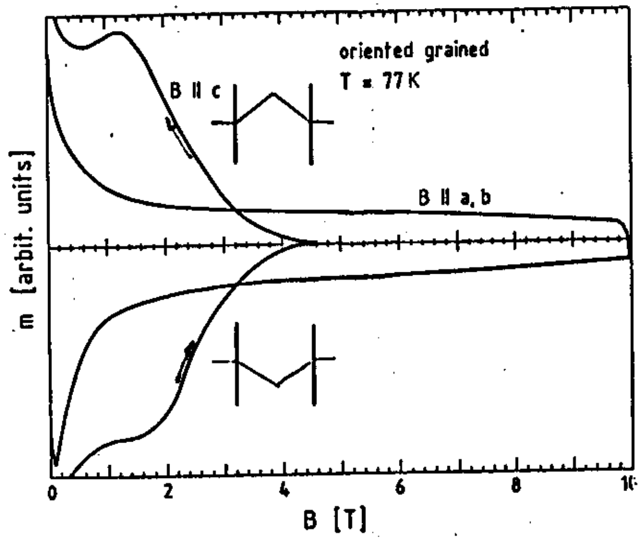
2) dc magnetization : shielding j_c



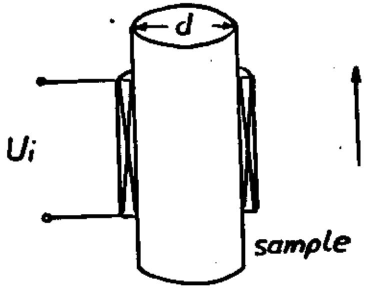
$$M_\downarrow - M_\uparrow = \Delta M = \frac{1}{3}\, j_c\, d$$

C.P. Bean

- $E \approx \frac{d}{2} \frac{dB}{dt} \gtrsim 10^{-4}\ \mu V/cm$
- Temperature variabel
- scaling length d
- flux jumps at low T

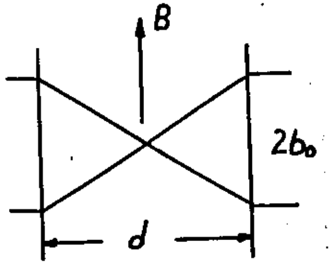


inductive measurements : shielding j_c



$B_{dc} + b_0 \sin \omega t$

3) ac susceptibility

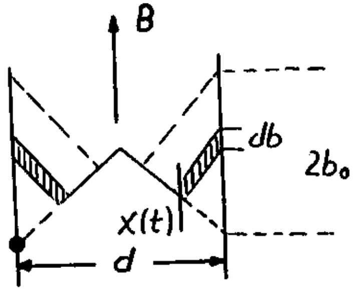


$$\chi'' \sim \int_{T/4}^{3/4 T} U_i \, dt$$

maximum of χ'' at

$$j_c = 2b_0 / \mu_0 d$$

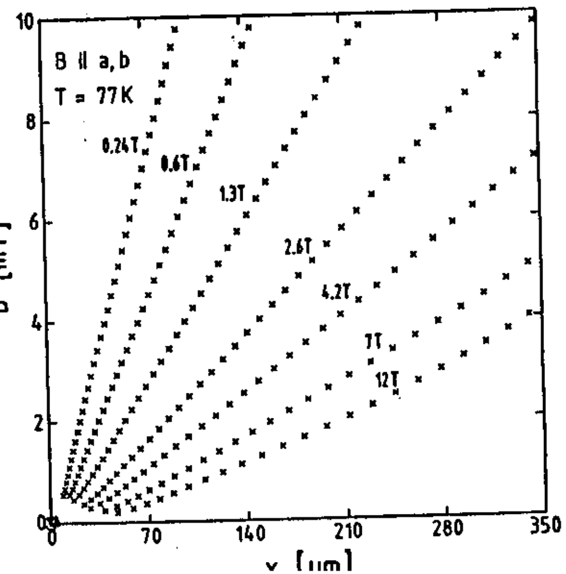
4) flux profile



$$U_i \sim \frac{d\phi}{dt} \sim \frac{db}{dt} \, x(t)$$

$$j_c = \frac{1}{\mu_0} \frac{db}{dx}$$

Rollins et al.



decoupling of the superconducting wave function at planar defects

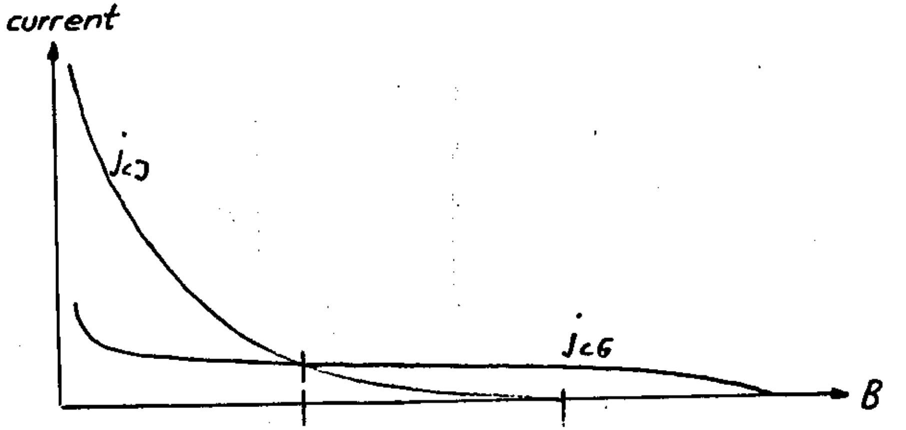
J.R. Clem

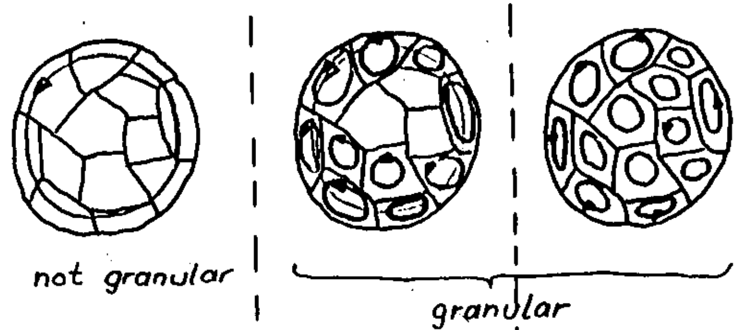
Deutscher and Müller

two current systems :

intragrain (bulk) current (pinning) j_{cG}

intergrain (weak link) " (coupling energy) j_{cJ}





$j_{cT} = j_{cS} = j_{cG}$ | $j_{cT} = j_{cJ} < j_{cS}$ | $j_{cT} = 0$, $j_{cS} = j_{cG}$

detection of granularity (two current systems)

transport:
- 1) B and T dependence of j_{cT}
- 2) $j_{cT}(B)$ history
- ● 3) comparison between j_{cT} and j_{cS} ●

dc shielding:
- 4) magnetization at $B < B_{c2J}$
- ● 5) j_{cS} (particle size) ●
- ● 6) comparison between $j_{cS}(\Delta m)$ and $j_{cS}(\Delta B)$ ●
- ● 7) "fish tail" in $j_{cS}(B)$ ●

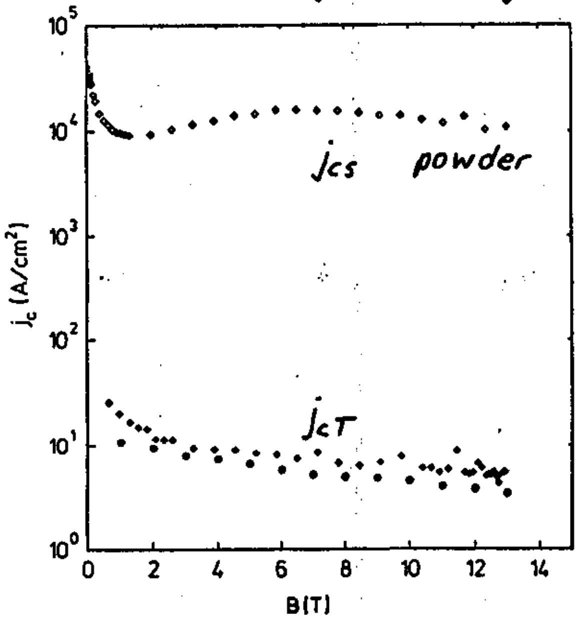
ac shielding:
- ● 8) ac susceptibility
- ● 9) flux profile
- 10) HF penetration depth ●

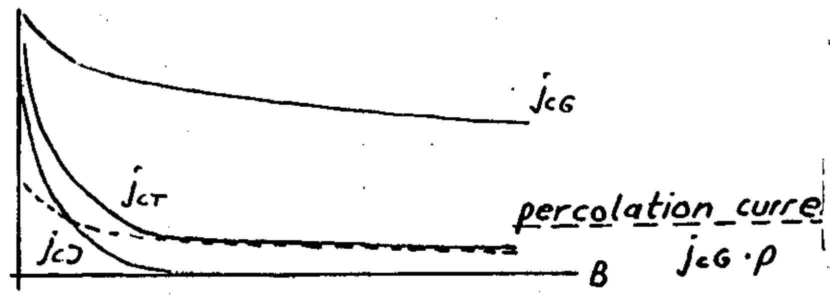
⋮

intragrain
weak links

polycrystalline $YBa_2Cu_3O_{7-x}$

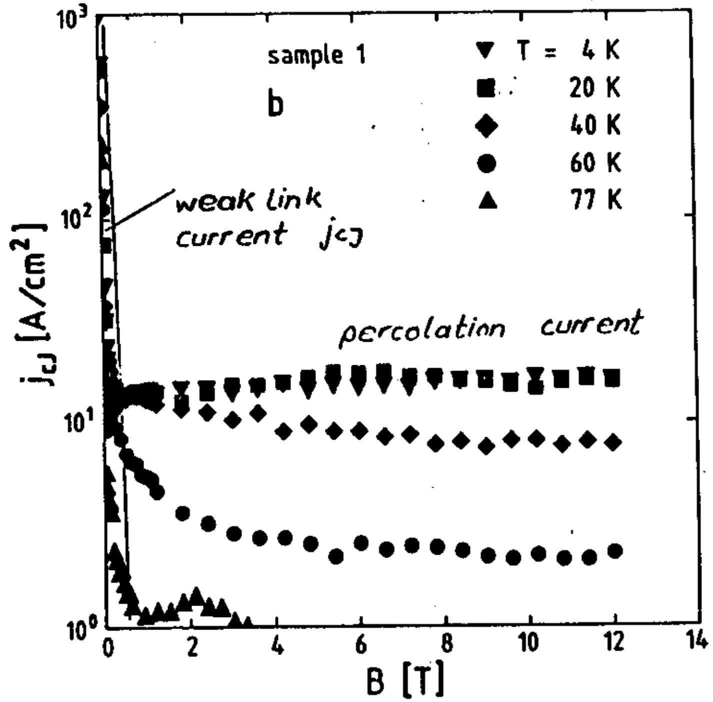
comparison between j_{cT} and j_{cS}





shielding current measurement requires d, but d(B,T) due to distribution of weak link properties

intergrain critical current density j_{cT} at high fields



weak link character $(j_{cJ} \sim B^{-1})$ vanishes at $B \geq 0.5T$

percolative current via superconduct. grain bound.

- no correlation of j_{cT} between low and high fields
- similar field dependence of j_{cT} and $j_{cS} = j_{cG}$
- $j_{cT}\,(\vec{B} \perp \vec{j}) \lesssim j_{cT}\,(\vec{B} \parallel \vec{j})$
- ac susceptibility : grain specific at high fields

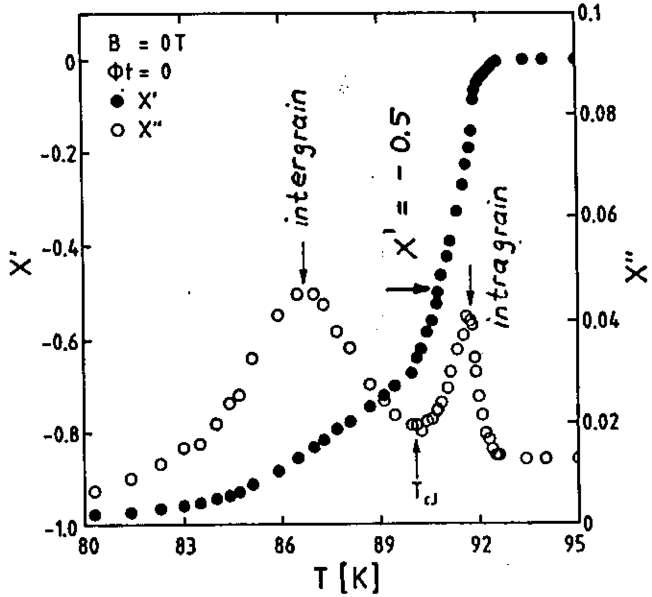
$YBa_2Cu_3O_{6.9}$ polycrystalline

density = 95 %

grain size = 25 μm   twin spacing = 0.12 μm

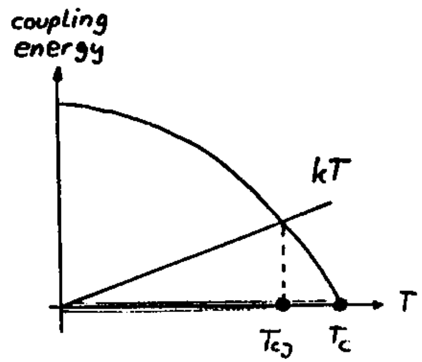
ρ (100 K) = 200 μΩ cm ρ (300 K) = 600 μΩ cm

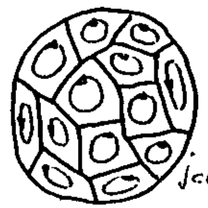
ac susceptibility   11 Hz , 1 Oe



superconducting grains weakly coupled at boundaries

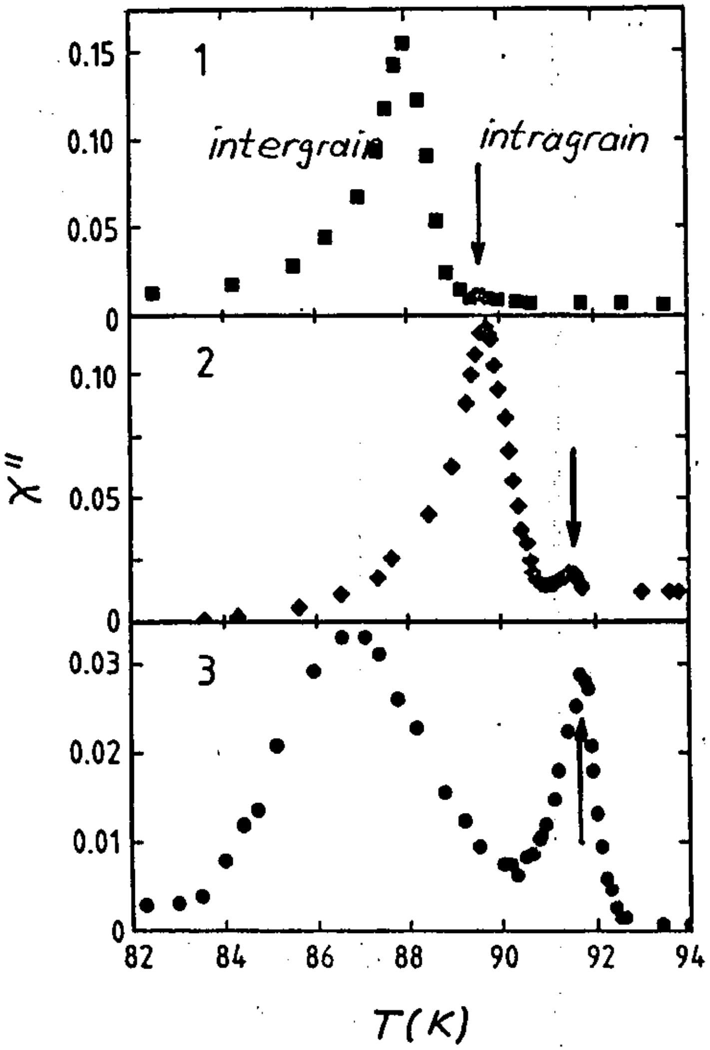
T < T_{cJ}





T_{cJ} < T < T_c

"double peak" structure depends on :
difference between j_{cG} and j_{cJ} , density , ...



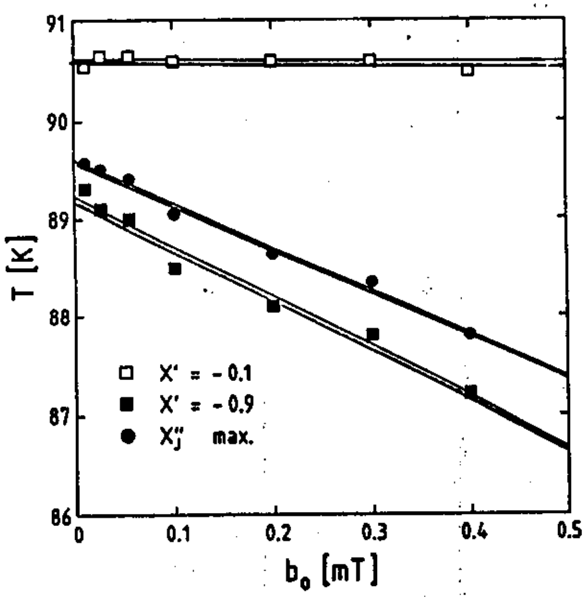
density :
75%

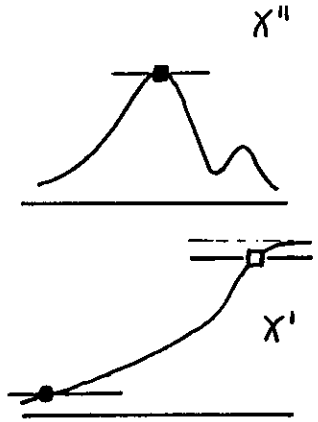
90%

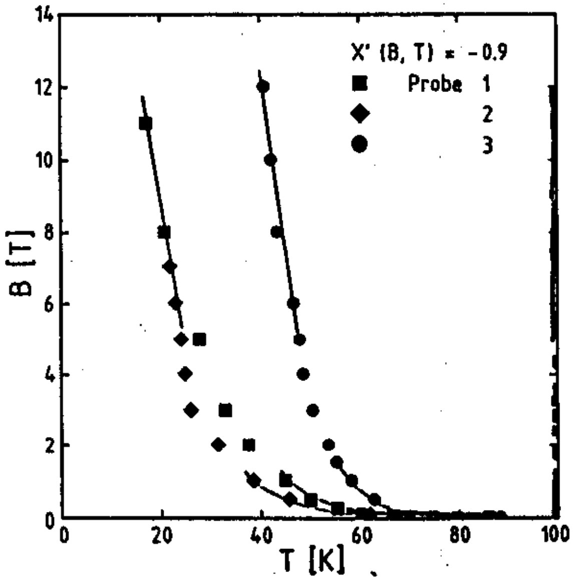
95%

high density , second phase content small
(" intergrain volume " small) ⇒
only intragrain peak detectable

variation of b_0, B_{dc}





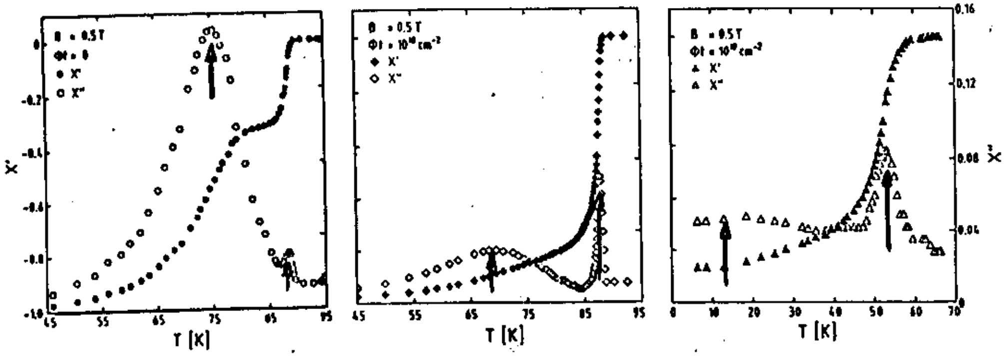


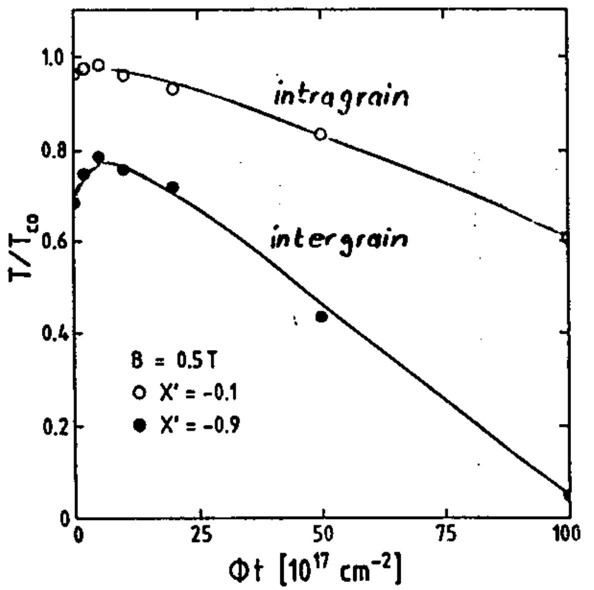
weak link character of
$\chi'(B,T)$ vanishes
at higher fields

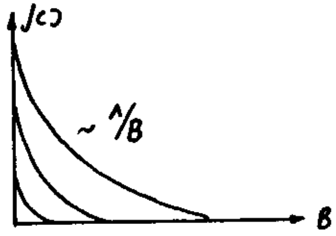
grain specific
$\frac{dB_{irr}(T)}{dT}$

neutron irradiation:

$\phi t = 0$ $\quad 10^{18}\ cm^{-2}$ $\quad 10^{19}\ cm^{-2}$



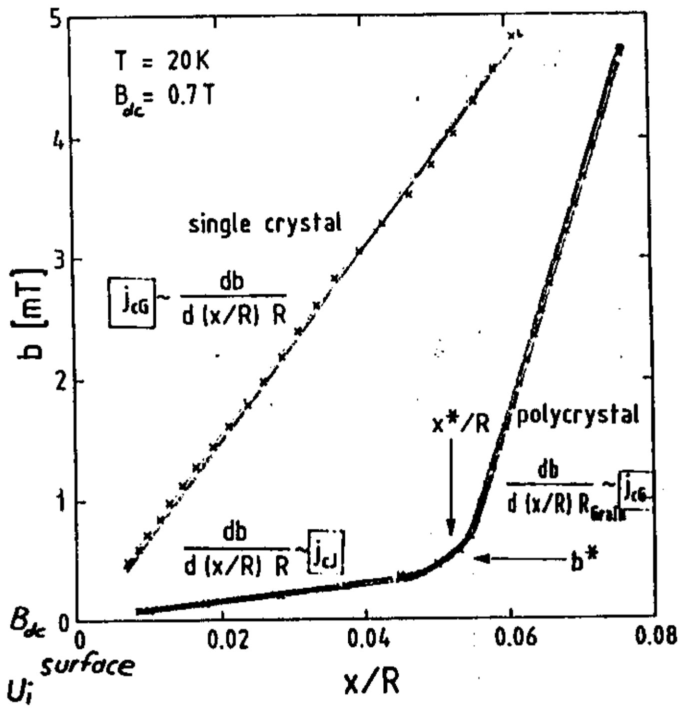


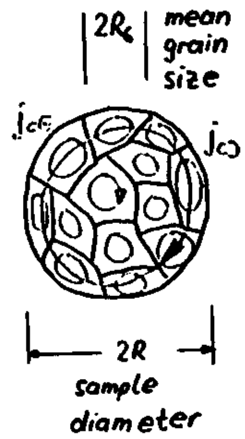


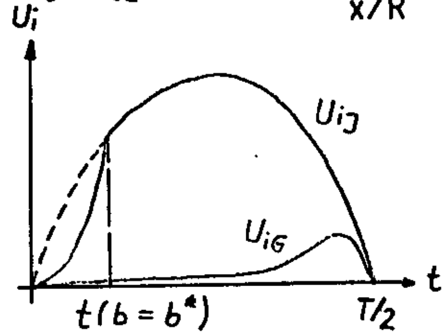
distribution of j_{cJ} becomes pronounced in applied B

radiation sensitivity of junction properties is larger than of grain properties especially in $B \neq 0$

flux profile measurement of inter- and intragrain current density







$$U_i = U_{iJ} + U_{iG}$$

$$j_{cG} R_G > j_{cJ} R$$

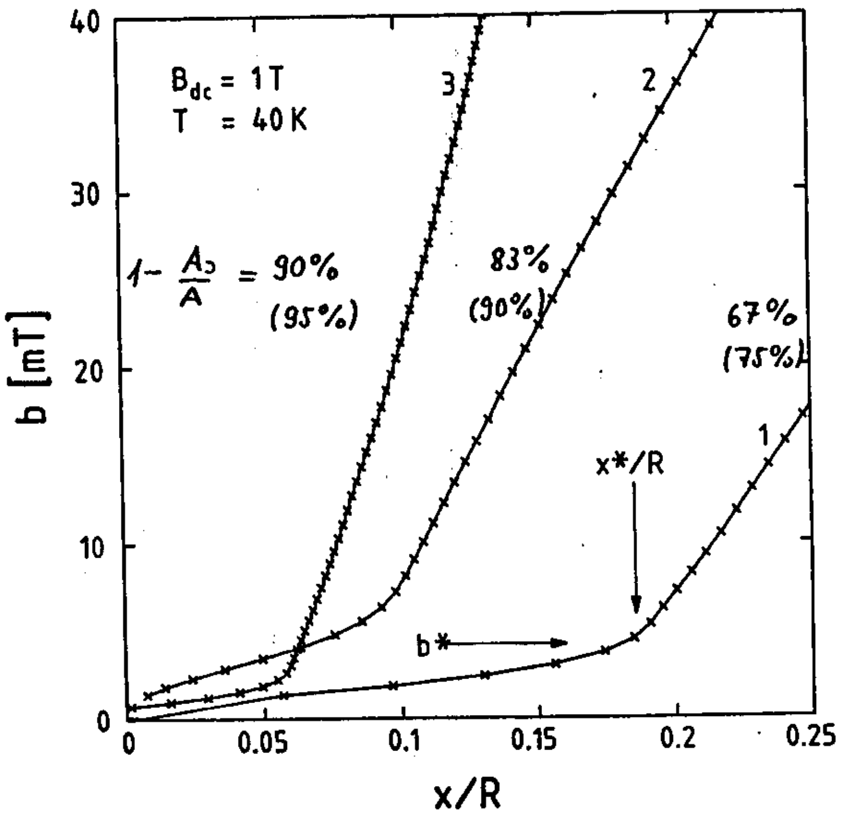
$b < b^*$	$b > b^*$
$U_i \approx U_{iJ} \gg U_{iG}$	$U_{iG} = U_i - U_i^{NC} A_J/A$
$j_{cJ} = \dfrac{db}{d(x/R)\, R} \dfrac{A_J}{A}$	$j_{cG} = \dfrac{db}{d(x/R)\, R_G}$

intergrain volume V_J

from flux profile measurement :

$$A_J = A - \pi (R - x^*)^2$$

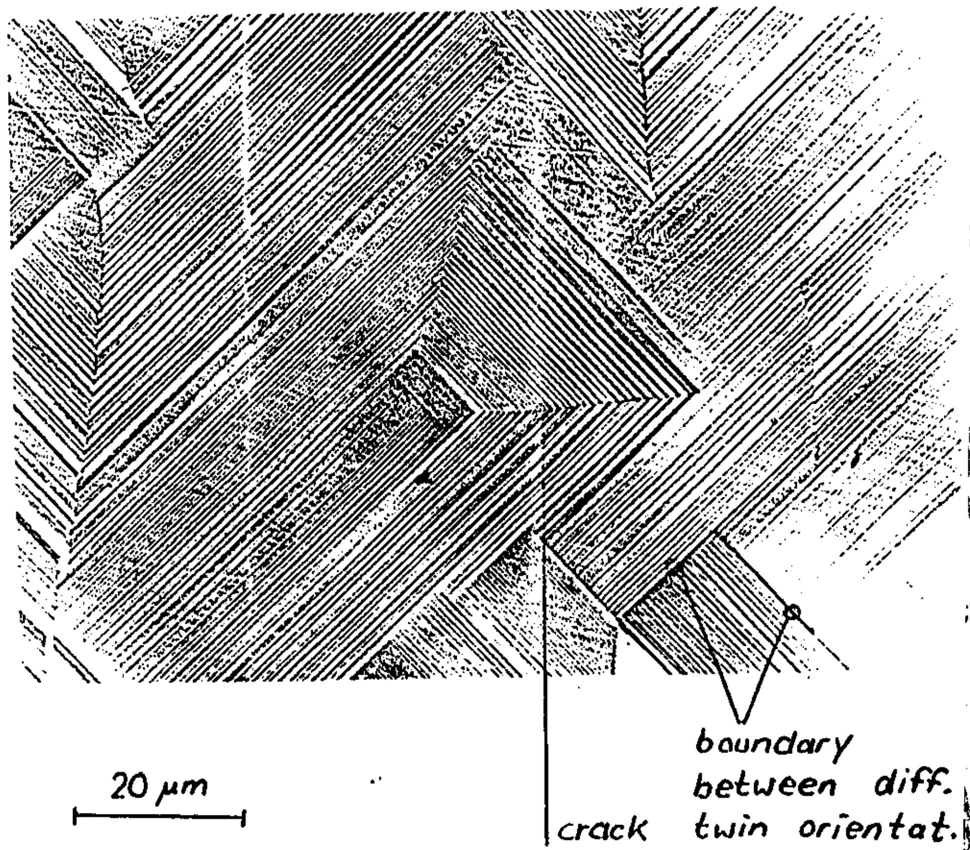
$$\frac{A_J}{A} = \frac{x^*}{R}\left(2 - \frac{x^*}{R}\right) = \frac{V_J}{V}$$



$YBa_2Cu_3O_{7-x}$ single crystal

possible intragrain weak links :

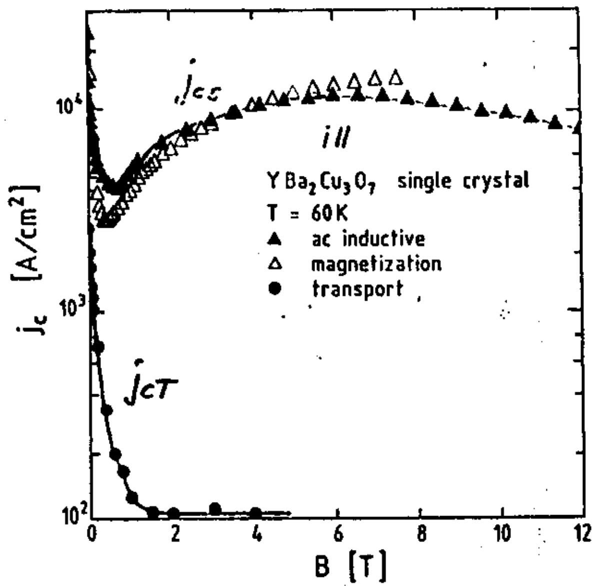
- twin boundaries
- stacking faults
- region of different twin orientation
- oxygen deficient regions
- microcracks



$YBa_2Cu_3O_x$ single crystal (grown in Al_2O_3 crucible)

$T_c = 84\ K$ $\rho(100K) = 0.15\ m\Omega cm$ $RRR = 3.5$

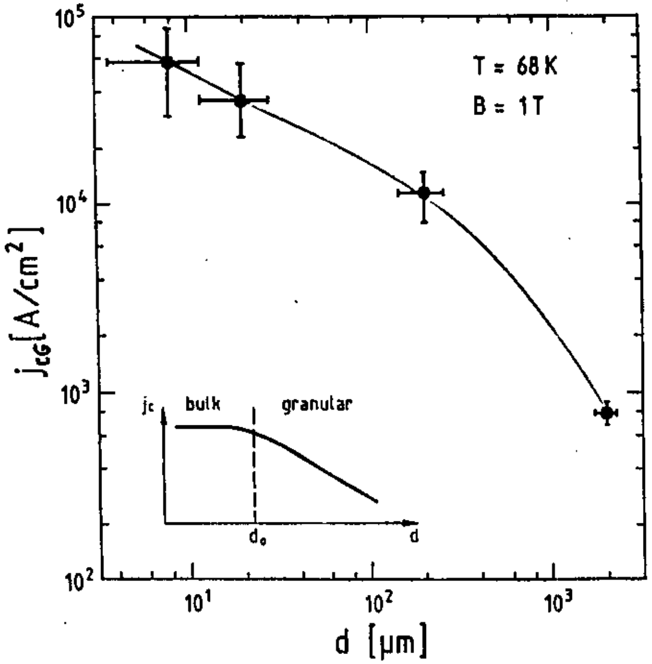
Wolf et al.



transport current << shielding current

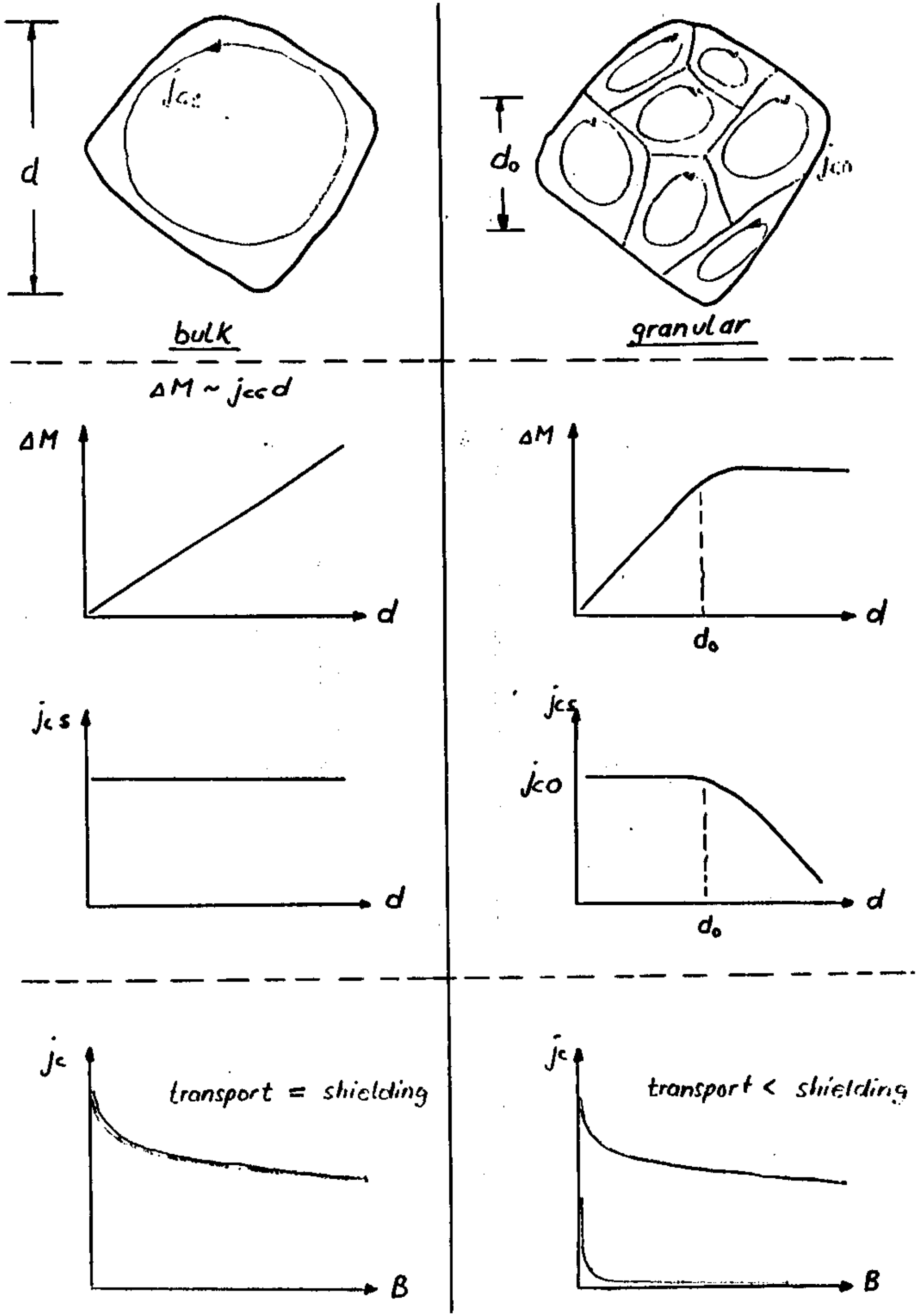
$\frac{j_{cT}}{j_{cs}}(B=0) \approx 10^{-1}$

$\frac{j_{cT}}{j_{cs}}(B>1T) \approx 10^{-2}$

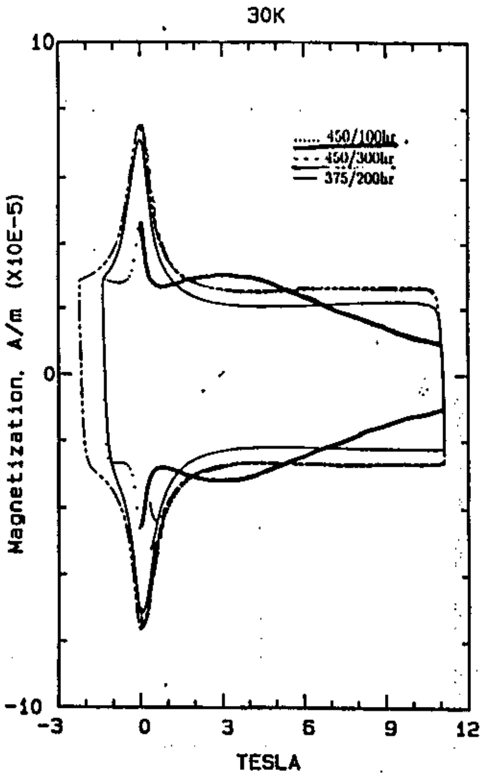


increase of the shielding current with decreasing powder particle sized

intragrain junctions determine the transport current



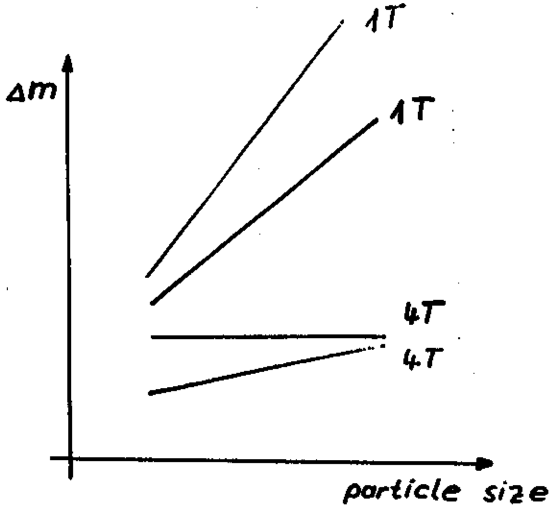
Larbalestier et al. $YBa_2Cu_3O_{7-\delta}$



$\delta \approx 0.05$

oxygen deficient region with lower T_c, B_{c2} determine granularity and pinning

with increasing oxygen content granularity vanishes and j_{cs} decreases



Δm does not extrapolate to zero : even at 0T

$j_{cs} > j_{cT}$

oriented grained $YBa_2Cu_3O_{7-x}$

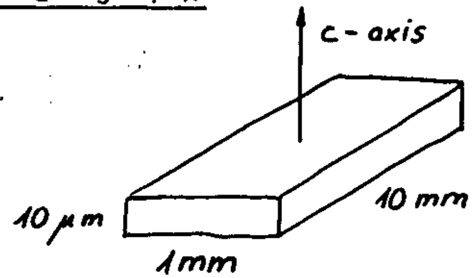
platelike grains are c-axis oriented

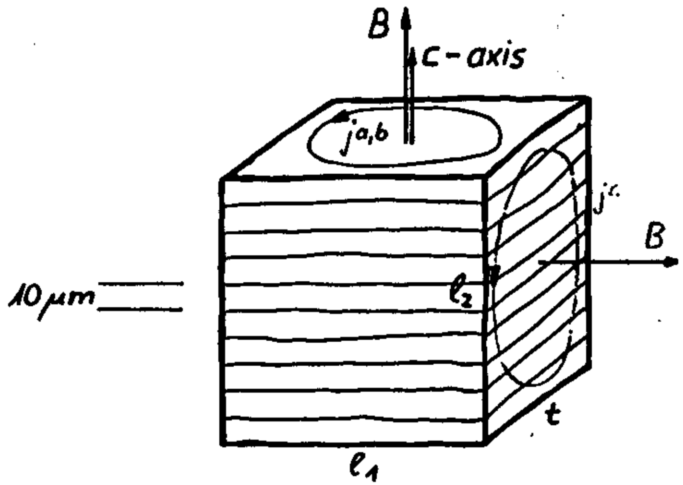
≈ 20% 211 phase

size of precip. ≥ 5 μm

twin spacing ≈ 0.1 μm

preparation : Salama et al.





$B \parallel c$ $\quad j \parallel a,b$

$B \perp c$ $\quad j \parallel c$ and $j \parallel a,b$

Gyorgy et al

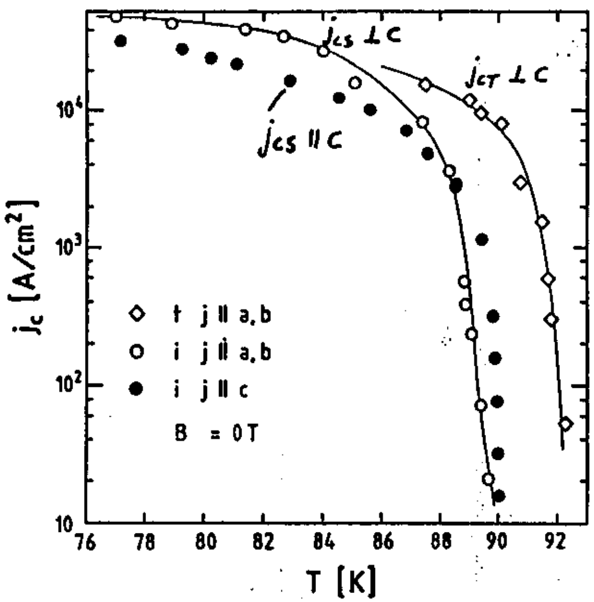
$\ell_1 \approx \ell_2 \approx 3.6$ mm

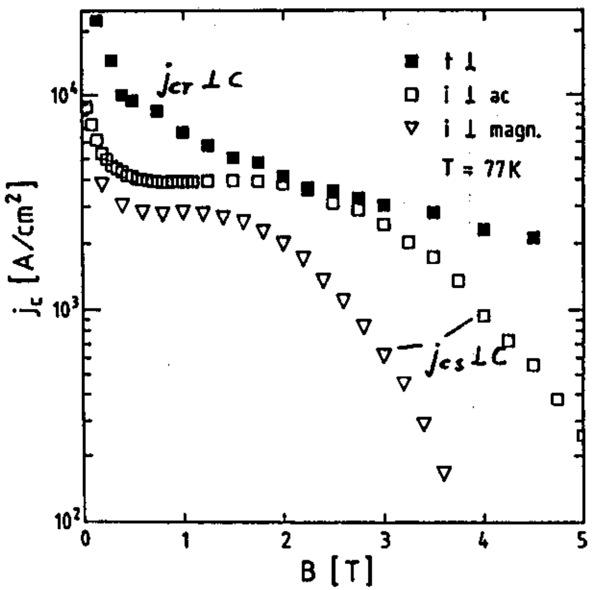
$t \approx 0.8$ mm

$$\Delta m_{\ell \perp c} \approx \frac{j^c t}{2}\left(1 - \frac{t\, j^c}{3\, \ell_2\, j^{a,b}}\right)$$

in both geometries { same demagnetization; same aspect ratio t/ℓ

comparison between j_{cT} and j_{cS} in $B \perp a,b$





$j_{cT} \approx j_{cS}$

different samples

" criteria

" misalignement between B and c-axis

no intragrain weak links in $j \parallel a,b$

Murakami et. al

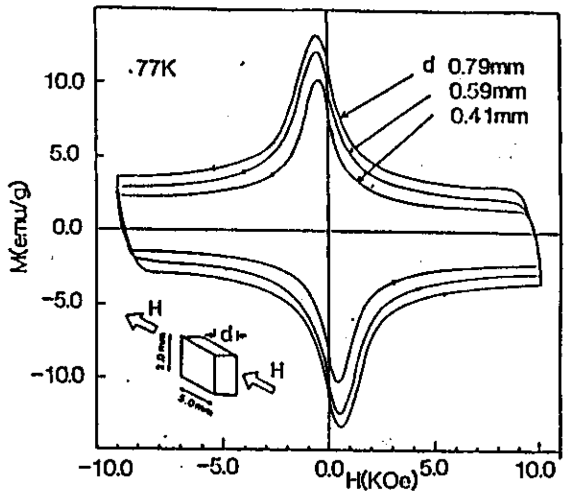
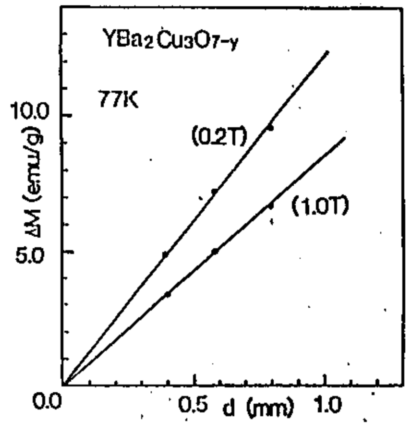


Fig. 4. Magnetization curves for YBaCuO quenched and melt processed. These data were taken as reducing the sample size.



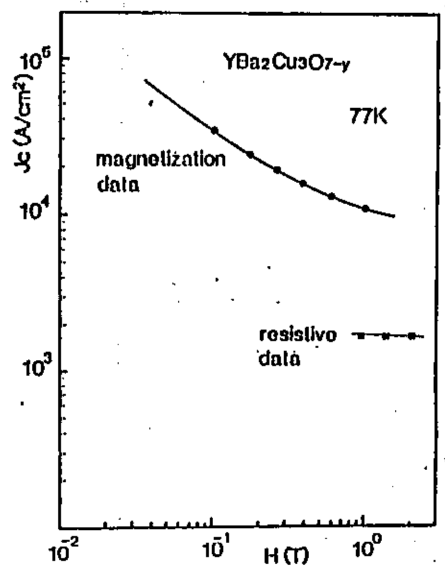
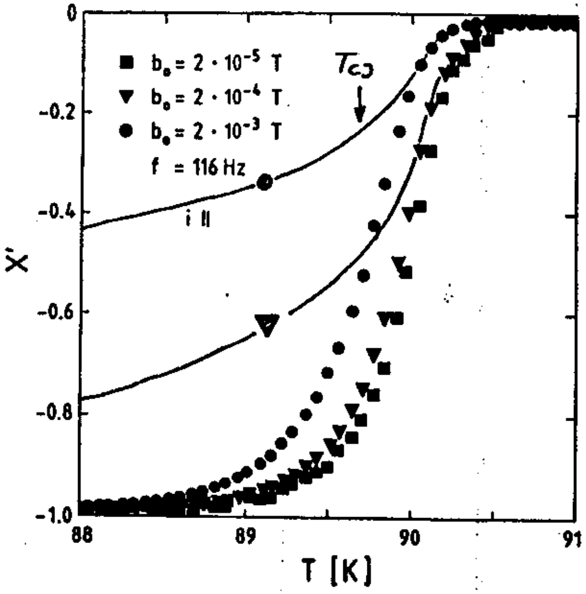


Fig. 5. Relationships between ΔM and d.

Fig. 6. Magnetic field dependence of critical current density .

Inter – and intragrain junctions ?

shielding current passes grain boundaries : $B \perp C$



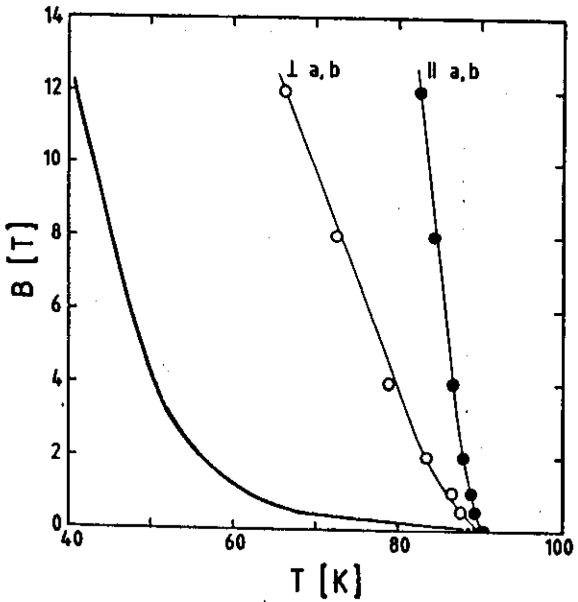
$\frac{dT}{db_o}$ $\left[\frac{K}{mT}\right]$

granular

– 10

oriented grained

– 0.2



$\chi' = -0.5$

11.6 Hz

10^{-4} T

o $j \parallel a,b$

• $j \parallel c$
grain boundaries passed

$B \parallel a,b$ $j \parallel c$

ac measurements do not show :

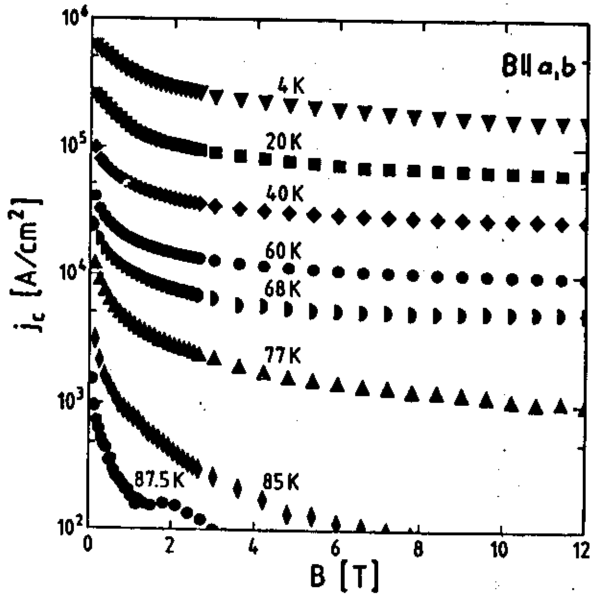
- two maxima in χ''
- pronounced shift of $\chi''(T)$ with b_o
- two j_c values in flux profile

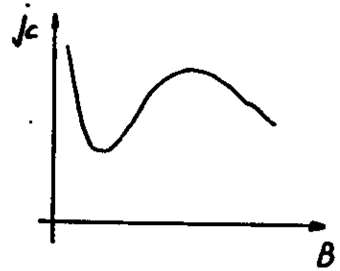
using grain size instead sample size :

$j_c \parallel c \approx 5 \cdot j_c \parallel a,b$

no decoupling at grain boundaries

decoupling within a grain ?





no "fishtail" effect in $j_c(B)$

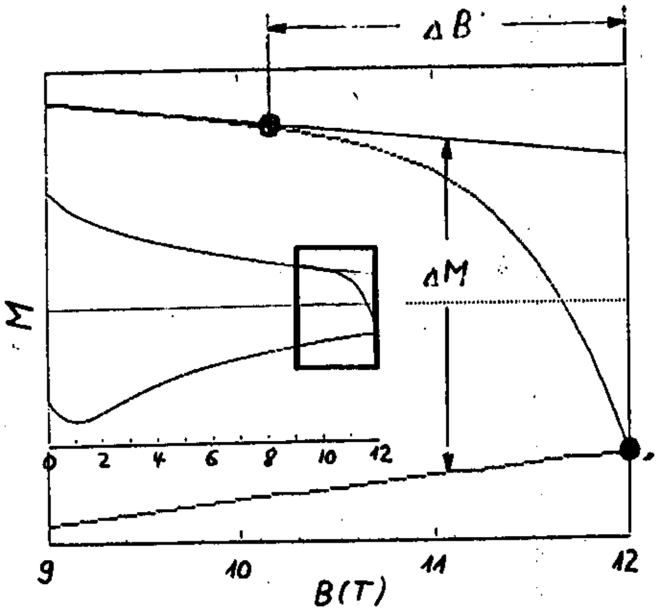
investigation of granularity
from deviation of uniform bulk current flow

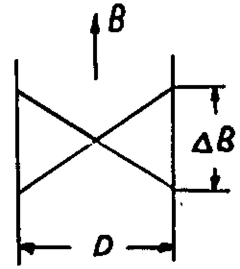
T. Matsushita

critical state model:

$$j_c(\Delta M) \approx \frac{3\,\Delta M}{D}$$

$$j_c(\Delta B) \approx \frac{\Delta B}{\mu_0 D}$$





$$\frac{j_c(\Delta B)}{j_c(\Delta M)} \approx \frac{\Delta B}{3\,\mu_0\,\Delta M} \approx 1$$

no surface pinning
correct geometry
j_c ≈ const. within ΔB
$D > \lambda'$

D cancels, no information about granularity ?

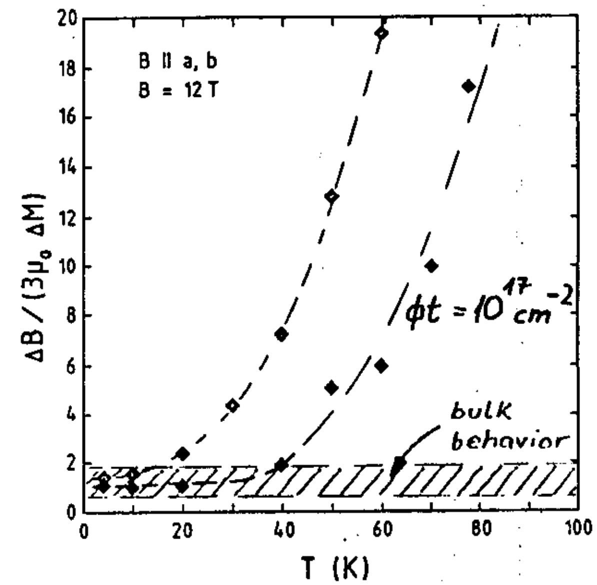
$$\frac{\Delta B}{3\,\mu_0\,\Delta M} > 1$$

in the case of partial decoupling, inhomogeneities percolation : nonuniform current flow, precursor of complete decoupling

$B \perp a,b$ $\qquad j \parallel a,b$

$$\frac{\Delta B}{3\,\mu_0\,\Delta M} \approx 1 \qquad \text{up to } 77\,K,\ 4\,T$$

$B \parallel a,b$ $\qquad j \parallel c$



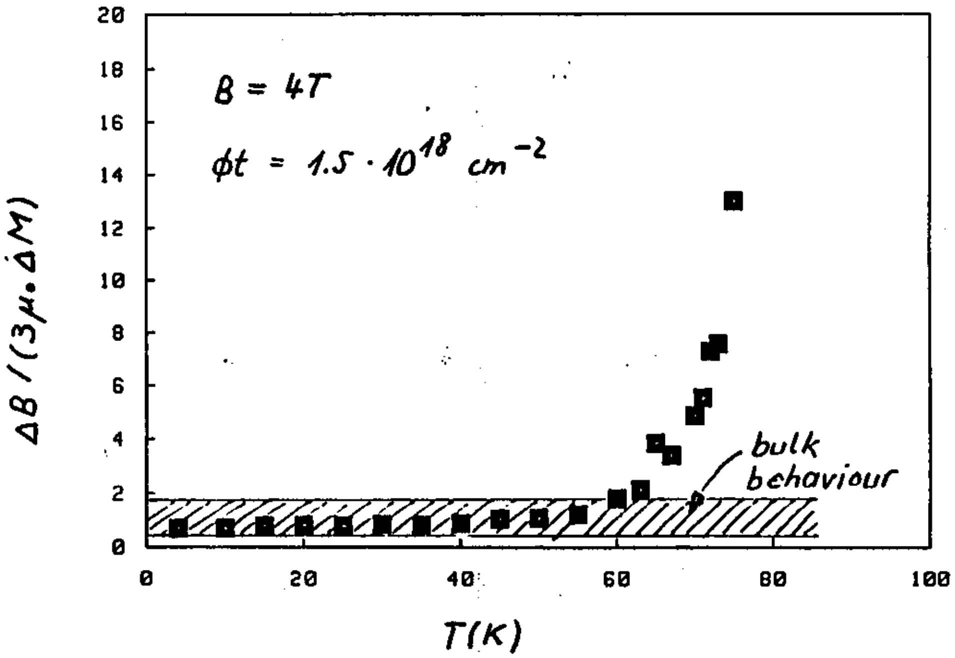
increasing deviation from homogeneous bulk current flow with B and T :

planar defects
oxygen def. regions

- addition oxygenation
- fast neutron irradiation

} decrease $\Delta B / \Delta M$

nonuniform current flow results from oxygen def. and inhomog. ox. distribution j ∥ a,b shows granular features at higher ϕt



intragrain weak links

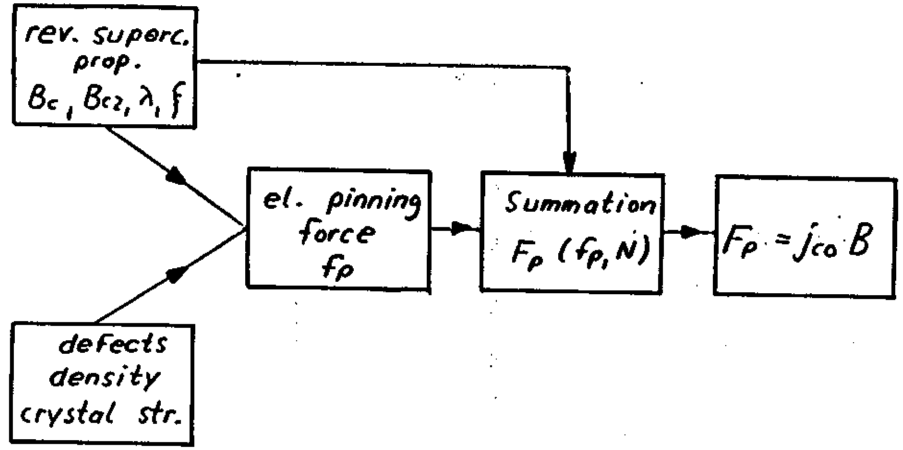
oxygen deficient regions
stacking faults ?
microcracks ?

intergrain weak links

grain boundaries

2) Flux pinning

improvement of j_c requires identification of the defect structure which is responsible for the measured j_c



usual way: (1) measurement of $j_c(B,T)$ and rev. properties and characteriz. of defect structure

(2) estimation of f_p (B,T)

(3) estimation of F_p (B,T) (summation problem)

(4) comparison of F_p (B,T) with measured j_c (B,T)

(5) variation of the defect structure F_p (N, defects)

Problems

- large number of different defects

  grain boundaries — orientation, second phases, stochiometry, oxygen content } diff. f_p

  twin boundaries

  stacking faults

  precipitates

  micro cracks

  porosity, microvoids

  stochiometry fluctuation

  oxygen deficient regions

  point defects

  dislocations

- variation of a certain defect structure changes other superconducting properties

- high T_c specific pinning mechanisms:

  intrinsic pinning

  pinning from point defects

- anisotropy of the superconducting prop.

  " of the defect structure

  $j \parallel a,b$ $B \parallel a,b$

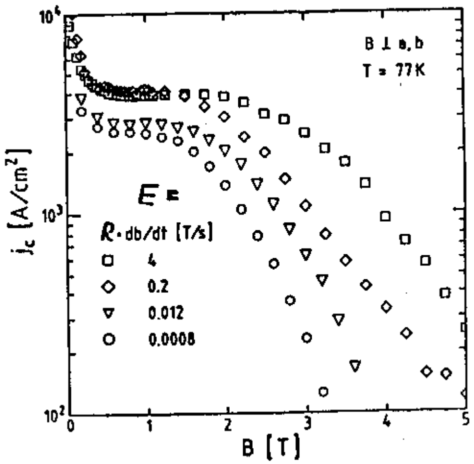
  $j \parallel a,b$ $B \parallel c$

  $j \parallel c$ $B \parallel a,b$

  } for $j \perp B$

- contribution from surface pinning in thin films

- measurements of $j_c(B,T)$ are influenced by relaxation, especially at higher T and B, but pinning models are based on unrelaxed current j_{co}



- comparison of the <u>pinning strength</u> in different geometries requires to eliminate the influence of different B_{c2}, $\varkappa$ and different reduced field B/B_{c2}

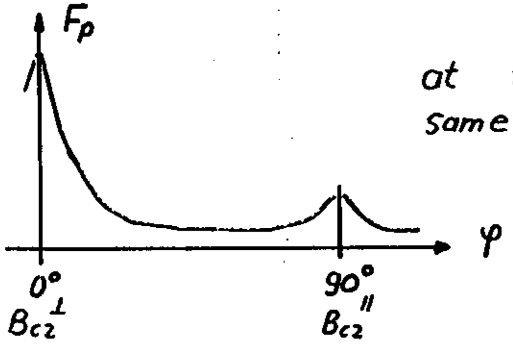
$$F_p(B,T) = K(\underline{\text{defect specific}})\,\underbrace{B_{c2}^{m}(T)}_{\text{temp.}}\ \underbrace{f(B/B_{c2})}_{\text{field}}$$

dependence

$$\frac{K^{\parallel}}{K^{\perp}} = \frac{F_p^{\parallel}(T_1, B_1/B_{c2}^{\parallel})}{F_p^{\perp}(T_2, B_2/B_{c2}^{\perp})}$$

with $\left[B_{c2}^{\parallel}(T_1)\right]^{m\parallel} = \left[B_{c2}^{\perp}(T_2)\right]^{m\perp}$

$$f(B_1/B_{c2}^{\parallel}) = f(B_2/B_{c2}^{\perp})$$



at the same B and T

$$\left(\frac{B_{c2}^{\parallel}}{B_{c2}^{\perp}}\right)^{m} \approx \begin{cases} 50 & \text{Y-Ba-Cu-O} \\ 10^3 & \text{Bi-Sr-Ca-Cu-O} \end{cases}$$

<u>variation of the defect structure</u>

(1) texture
melt processing

(2) 211 inclusion from liquid

(3) radiation damage

(4) doping with Fe, Zn, ...

(5) oxygenation

(6) alloying with Ag

(7) precipitates

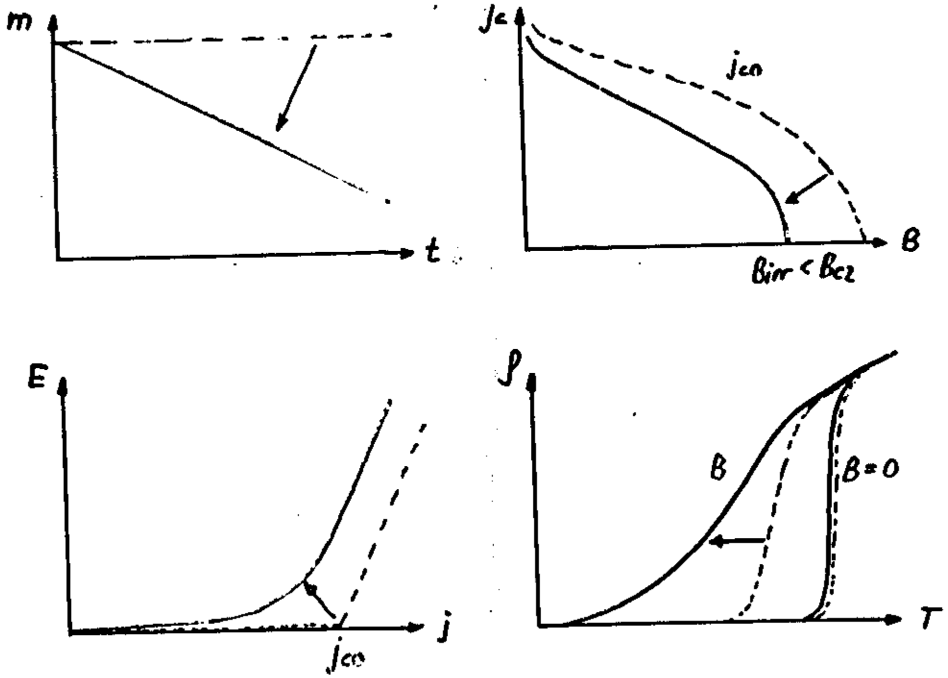
⋮

granularity and pinning cannot strictly separated. The same defect may act as pinning centre and as weak link in different geometry, B or T region

A.M. Campbell

3) Relaxation

experimental observations :

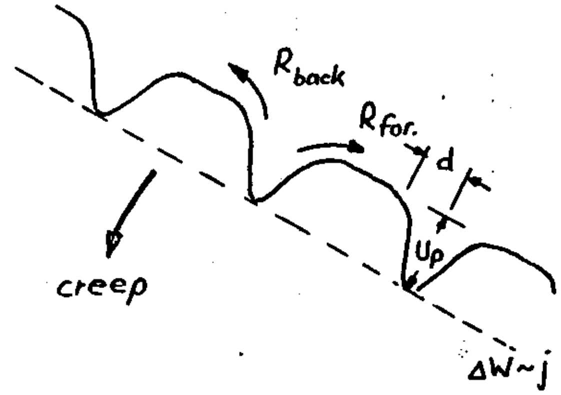


- time dependent decay of the current by frustration or junction resistivity

- time dependent decay by thermally activated flux creep

- fluctuation , flux lattice melting , ...

thermally activated flux creep :



U_0 : activation energy

U_p : pinning pot.

d : potential width

V : flux bundle volume

Ω_0 : attempt frequ. ($10^6 \div 10^{12}$ Hz)

Anderson
Beasley et al.
Campbell and Evetts
Dew Hughes
Griessen

$$U(t) = U_0 - \Delta W(t)$$

$$\Delta W = j B d V$$

$$U(j) = U_0 \left(1 - \frac{j}{j_{c0}}\right)$$

hopping rate :

$$R_{for.} = \Omega_0 \, e^{-(U_0 - \Delta W)/kT}$$

$$R_{back} = \Omega_0 \, e^{-(U_0 + \Delta W)\, kT}$$

$$R_{res.} = 2 \Omega_0 \, e^{-U_0/kT} \sinh \frac{\Delta W}{kT}$$

$$\vec{E} = \vec{v} \times \vec{B}$$ electric field due to flux movement

$$E = R_{res.} \, a_0 \, B$$ a_0 : flux line distance = hopping distance

$\underline{U_0 \gg kT}$

(1) $j_{c0} \geq j \geq j_{c0} \frac{kT}{U_0}$ $\quad (\Delta W \gg kT)$

$$E = a_0 B \Omega_0 \, e^{-\frac{U_0}{kT}\left(1 - \frac{j}{j_{c0}}\right)} \sim e^{j}$$

(2) $j \leq j_{c0} \frac{kT}{U_0}$ $\quad (\Delta W \leq kT)$

$$E = 2 \frac{U_0}{kT} \frac{a_0 B \Omega_0}{j_{c0}} e^{-\frac{U_0}{kT}} j \sim j$$

Maxwell, Bean : $E = -\frac{1}{2} \mu_0 R \frac{dM}{dt}$

(1)

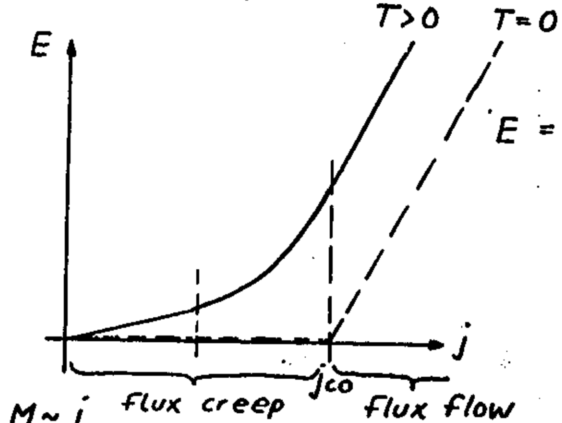
$$\boxed{M = M_0 \left(1 - \frac{kT}{U_0} \ln\left(1 + \frac{t}{\tau_0}\right)\right) \sim \ln t \qquad \tau_0 = \frac{1}{6} \mu_0 R^2 \frac{kT}{U_0} \frac{j_{c0}}{E_0}}$$

(2) $M = M_0 \frac{kT}{U_0} e^{-2(t-\tau_c)/\tau_c} \sim e^{-t}$

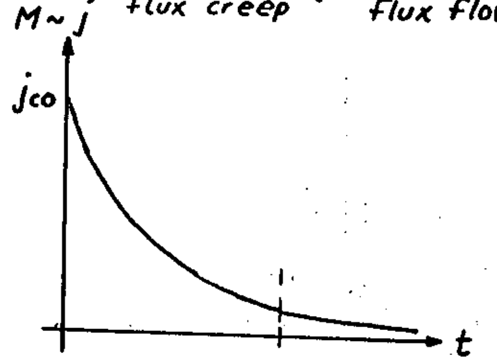
$$\tau_c = \tau_0 \, e^{U_0/kT}$$

Keller et al.

$\underline{U_0 \gg kT}$



$E = \rho_F (j - j_{c0})$



(1) $j_{c0} \geq j \geq j_{c0} \frac{kT}{U_0}$

$\underline{E \sim e^{j}}$

$\underline{M \sim j \sim \ln t}$

(2) $j \leq j_{c0} \frac{kT}{U_0}$

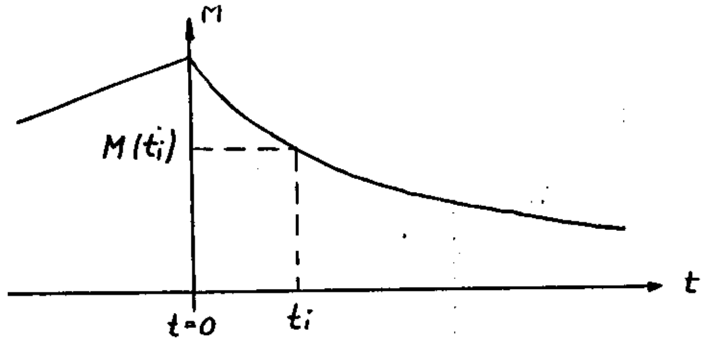
$\underline{E \sim j}$

$\underline{M \sim j \sim e^{-t}}$

$\underline{U_0 \approx kT}$

$$E = 2 \frac{U_0}{kT} \frac{a_0 B \Omega_0}{j_{c0}} e^{-U_0/kT} j$$

$$M \sim j = j_{c0} \, e^{-t/\tau_s}$$



$$\frac{U_0}{kT} = \frac{M(t=0)}{dM/d\ln t} = \underbrace{\frac{1}{\left[1 - \frac{kT}{U_0}\ln\left(1+\frac{t_i}{\tau_0}\right)\right]}}_{\text{decay within } 0 \le t \le t_i} \frac{M(t_i)}{dM/d\ln t}$$

$$\tau_0 \approx \Omega_0^{-1} \approx 10^{-12} \div 10^{-6}\ s$$

$$\tau_0 = \frac{1}{6}\mu_0 R^2 \frac{kT}{U_0}\frac{j_{c0}}{E_0}$$

typical values for $YBa_2Cu_3O_{7-x}$ ($B \ll B_{irr}$)

$$\frac{U_0}{kT} = 10$$

$$j_{c0} = 10^4\ A/cm^2$$

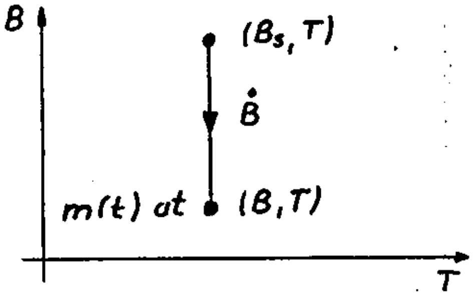
$$E_0 = 1\mu V/cm$$

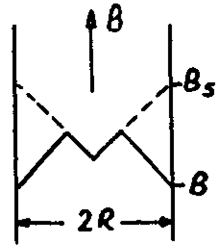
$$R = 1\ mm$$

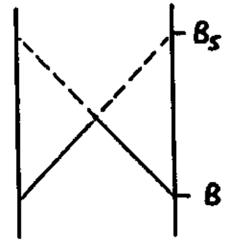
result in $\underline{0.1\ s \lesssim \tau_0 \lesssim 10\ s}$

$m(t)$ measured at B, T depends on

(1) history: B_s, T_s, $\dot{B}$, $\dot{T}$







Matsushita et al.

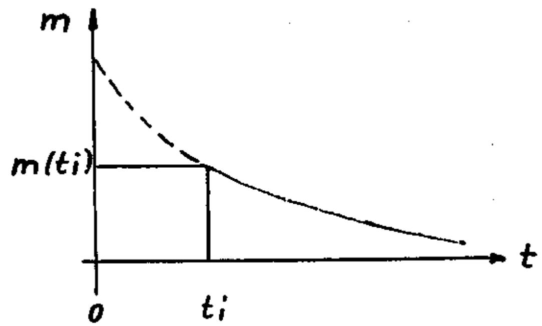
Moshchalkov et al.

$$(B_s - B) > \mu_0 j_c 2R$$

$$(B_s - B) \approx 3\ T$$

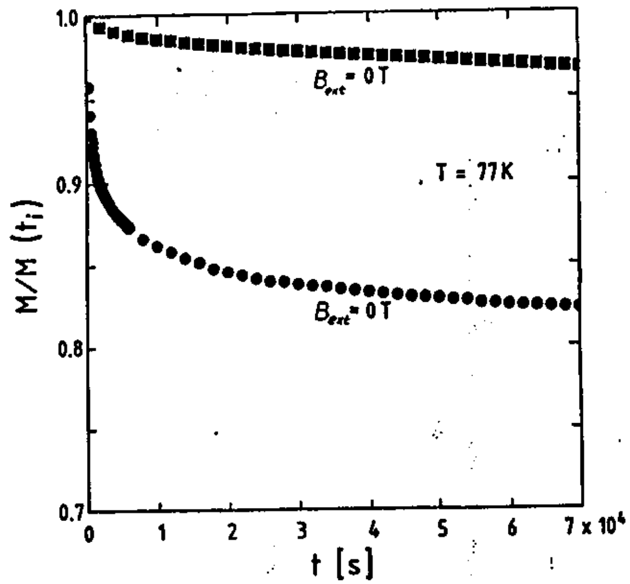
$\dot{B} \approx 0.012\ T/s$ not sufficient in the vicinity of B_{irr}

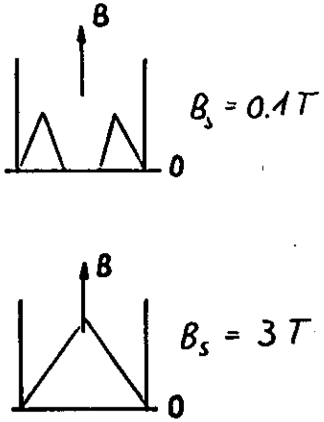
(2) time t_i

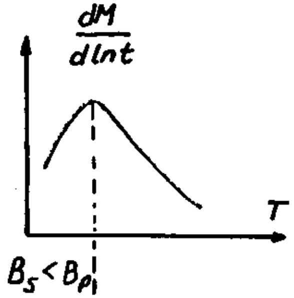


first measurement of m at t_i

$$t_i \approx 15\ s$$



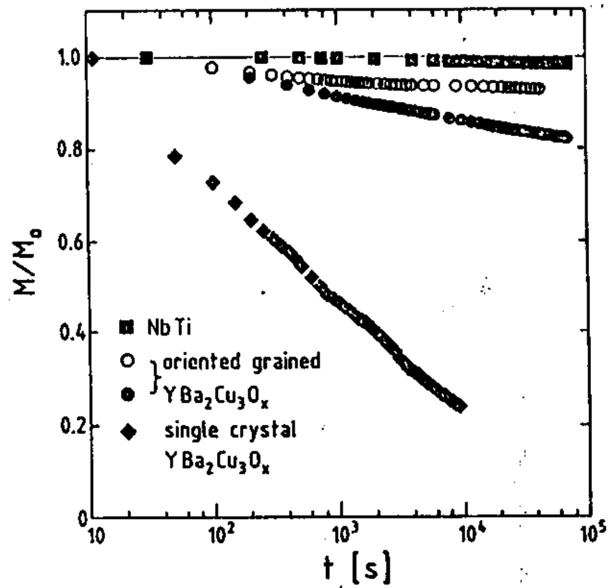




Comparison with Nb 49 wt. % Ti

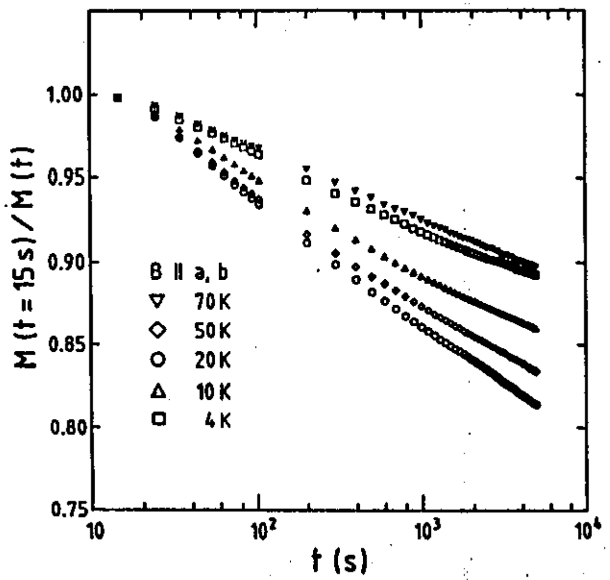
$T_c \approx 9K$

j_c (4.2K, 0T) $\approx 3.5 \times 10^5$ A/cm²



B = 0 T

- ■ 4.2 K
- ○ 77 K j ∥ a,b
- ◉ 77 K j ∥ c
- ◆ 60 K j ∥ a,b



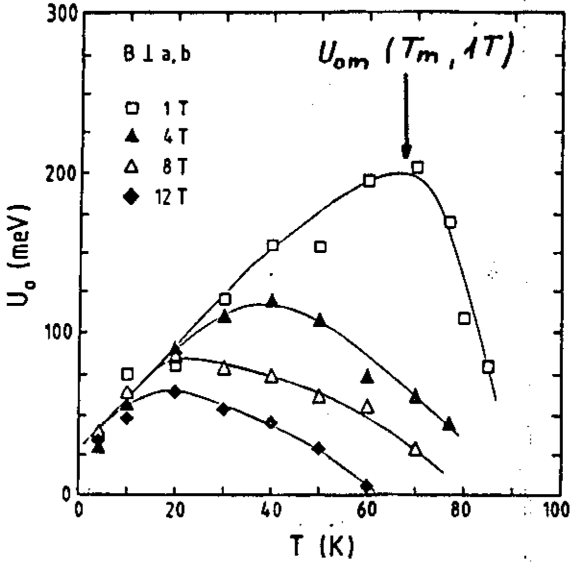
deviations from a logar. decay of M :

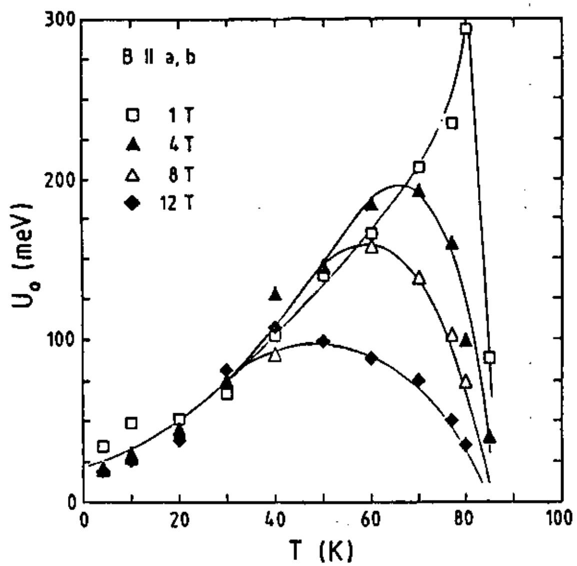
(1) $t \leq 50s$

(2) in the vicinity of B_{irr} ($U_o \geq kT$)

		U_o / kT	U_o [meV]	ρ [$\mu\Omega$ cm]
oriented grained $YBa_2Cu_3O_x$ 77K	j ∥ c	41	272	
	j ∥ a,b	55	365	10^{-9}
Nb 49 Ti	4 K	4.87	176	10^{-12}
	7.5 K	182	118	
$YBa_2Cu_3O_x$ single crystal with intragrain junctions	60 K	8	41	

$$\frac{U_0}{kT} = -\frac{M(t_i)}{dM/d\ln t} \qquad \frac{1}{\left[1 - \frac{kT}{U_0}\ln\left(1 + \frac{t_i}{\tau}\right)\right]} < 2$$





$U_0(B,T)$ behaviour :

(1) $U_0(T)$ increases with T up to U_{om} $(T = T_m)$

(2) T_m and U_{om} decrease with B

(3) above T_m U_0 approaches T_{irr} at which $U_0 \approx kT$

$T \lesssim T_m$

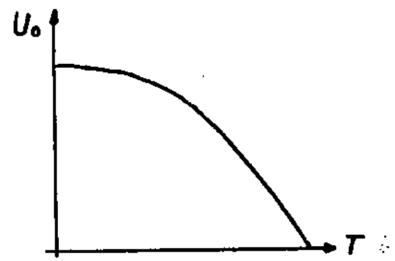
$30 \lesssim U_0/kT \lesssim 80$

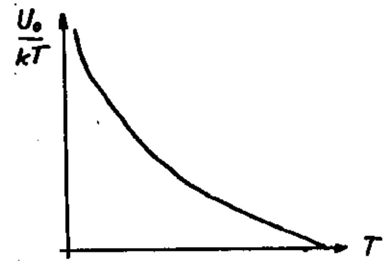
comparable with low T_c supercond.

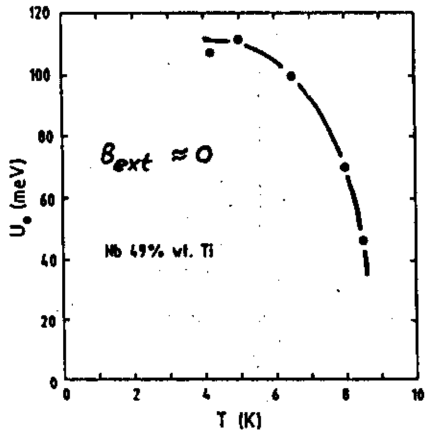
<u>expected</u> $U_0(B,T)$ from

(1) $j_c(B,T)$ similar as $U_0(U_p)$

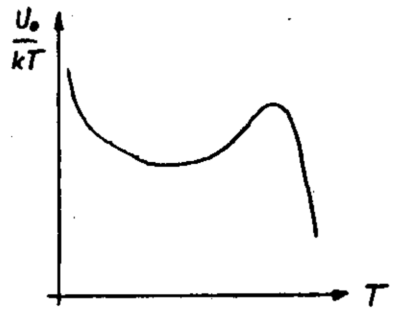
(2) low T_c superconductors







<u>observed</u>



explanations for $U_0(T)$

(1) distribution $F(U_0)$ neglected

(a) single vortex activation

→ (b) flux bundle activation
Fujiyoshi et al.

→ (c) nonlin. $U(j)$ relation Suenaga et al.
Maley et al.
Welch

(2) distribution $F(U_0)$ dominant

(a) j_c distribution, $E \sim j^n$ Sun et al.

→ (b) exp. time scale determines measured part of $F(U_0)$
Hagen and Griessen

→ (c) percolation path in $F(U_0)$
Gurevich et al.

→ (3) change of pinning structure
Keller et al.

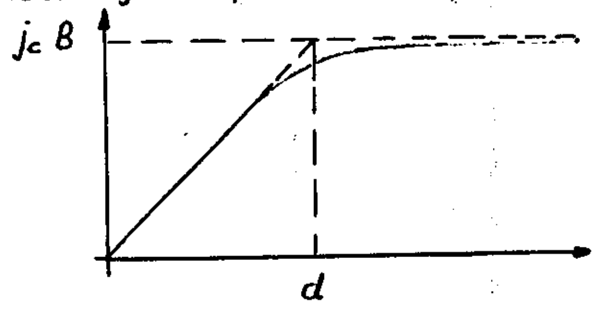
$U_0(T)$ due to collective interaction :

$U_0 \neq U_p \Rightarrow$ thermal activation of flux bundles

$$j_c\, B\, d = \hat{U}_0 = \frac{U_0}{V}$$

V = flux bundle volume

d = reversible displacement



A.M. Campbell

$$V \sim \frac{T}{dM / d\ln t}$$

$V \mathrel{\hat{=}} V_c$ correlation volume of the collective theory
Kes et al., Matsushita

$V_c(T) \sim \tilde{L}_c(T)$ nonlocal limit

$$\tilde{L}_c(T) \sim \left(\frac{B_{c2}^2(T)}{\varkappa^4(T)\; f_p^2(T)} \right)^{1/3}$$ Larkin and Ovchinnikov

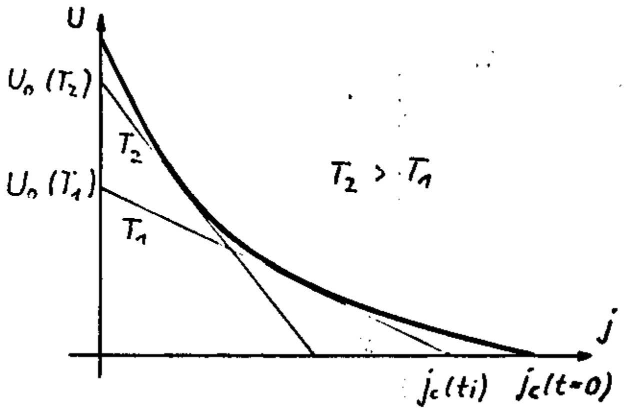
$f_p \sim B_c^2\, \xi^m$ core interaction

$V(T) \sim \tilde{L}_c(T)$ increases for $m < 2$

(1c) nonlinear $U(j)$ relation

Maley et al.

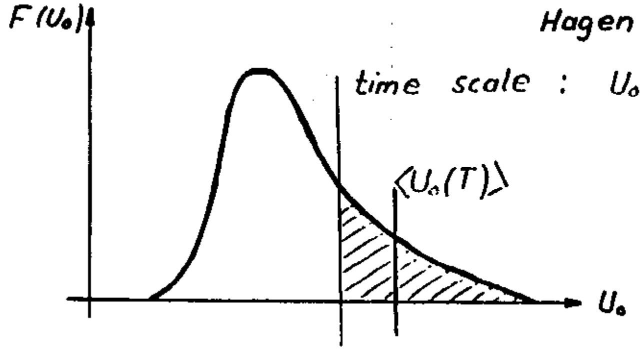
Welch



decay of j_c from $j_c(t=0)$ to $j_c(t_i)$ increases with T

(2b) experimental time scale determines measured part of $F(U_0)$

Hagen and Griessen



statistically independent relaxation

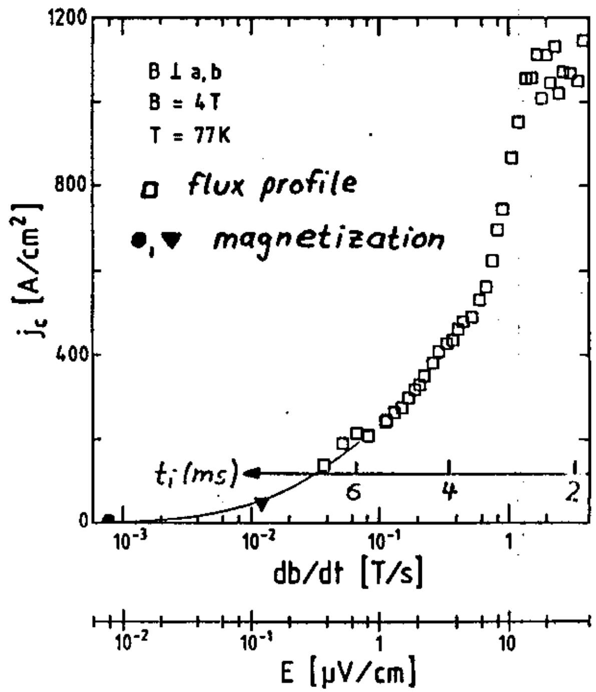
$\langle U_0(T) \rangle$ increases with T

both explanations predict :

- non log. time dependence of M
- variation of $M(t_i) \sim j_c(t_i)$ with time scale

flux profile measurement in dependence on $db/dt \sim b_0 f$

shift t_i into ms regime



above $U_{om}(T_m)$ rapid decay of j_c

<u>but</u>

j_c independent of t_i below $U_{om}(T_m)$

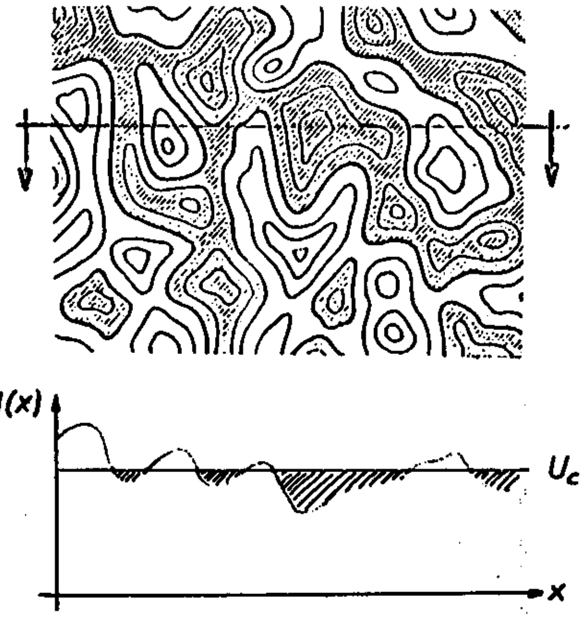
60K , 10 T :

$j_c = (10200 \pm 200)\,A/cm^2$

(2c) distribution of U

but relaxation <u>not</u> statistically independent

Gurevich et al.



2 dim. map $U(\vec{r})$

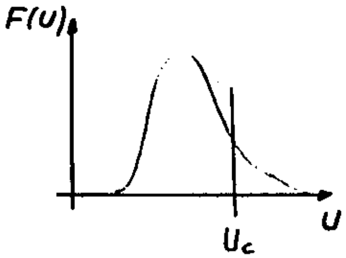
$$\rho(\vec{r}) = \rho_0 \, e^{-U(\vec{r})/kT}$$

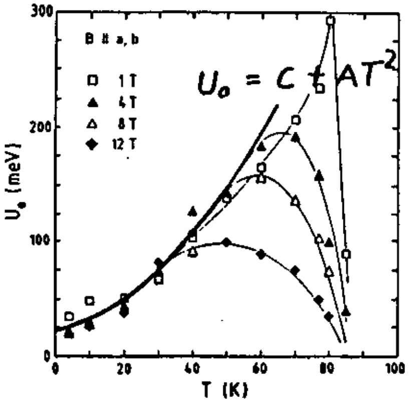
thermally activated depinning occurs first at the percolation threshold U_c

from eff. medium theory and arbitrary $F(U,B,T)$:

$$U_0(B,T) = U_c \, y(B,T) - \frac{\pi^2}{6} \frac{T^2}{y(B,T)} \left. \frac{dF/dU}{F} \right|_{U=U_c}$$

for low T $\quad y(B,T) \approx y(B,0) \approx$ const





(3) change of pinning structure

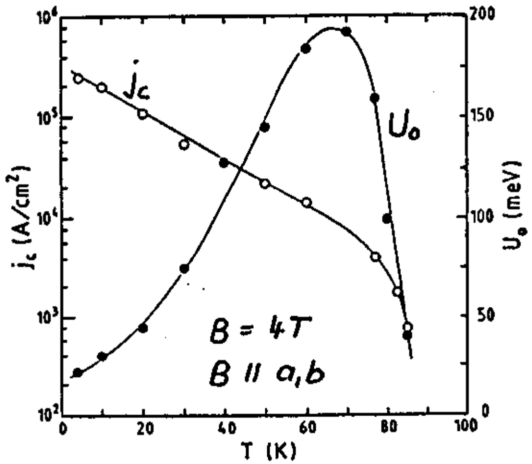
Keller et al.

oxygen deficient regions become normal conducting with B and T

Däumling et al.

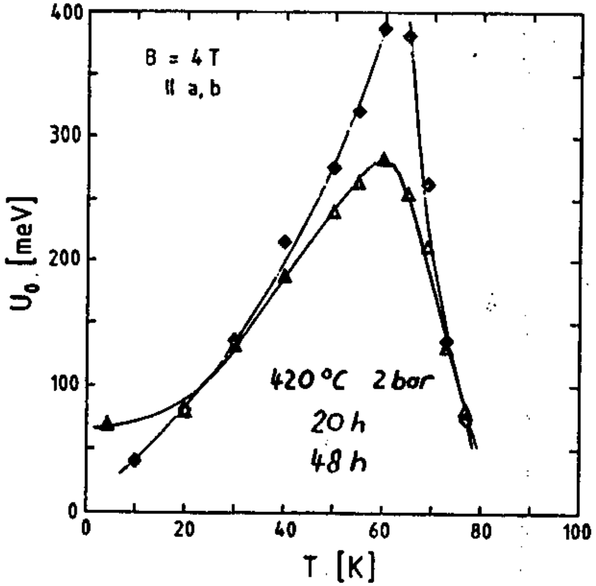
$U_0(T)\uparrow$: additional pinning and restricted flux movement

$j_c(T)\downarrow$: decrease with T is less fast than without add. def.



above the maximum of U_0 j_c decreases faster than $e^{-\alpha T}$

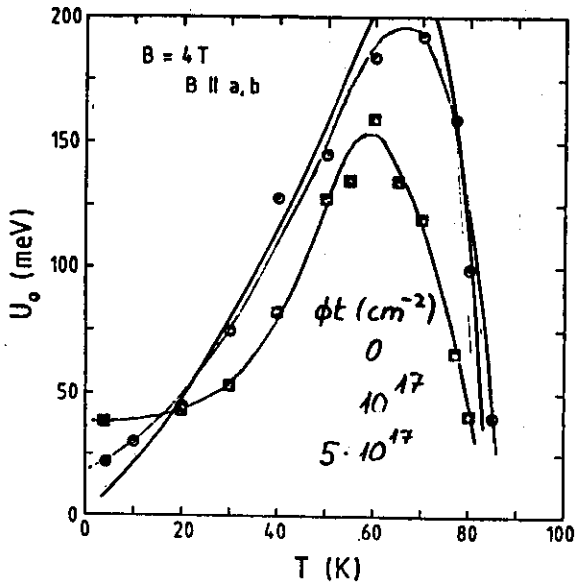
oxygen loading and n-irradiation result in similar change of U_0



U_0 :

increase at low T

decrease at T_m

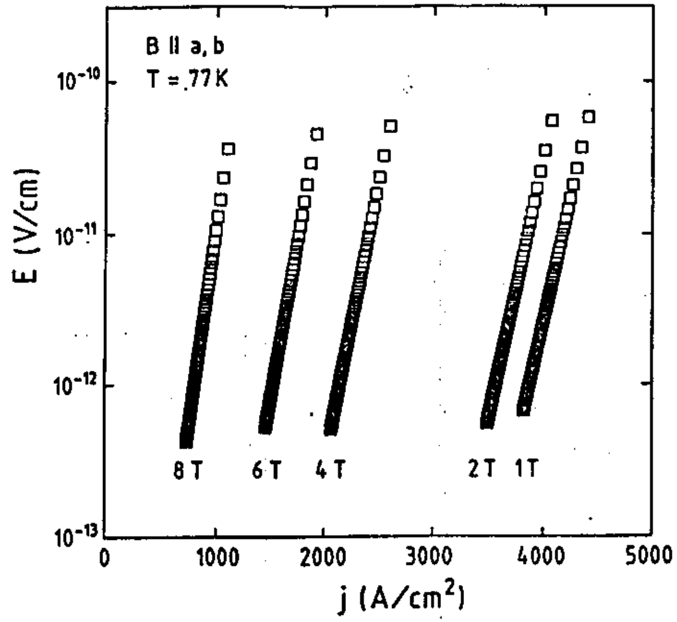


more homogeneous oxygen distribution reduces percolation threshold and restricted flux movement

Resistivity from magnetic relaxation:

$$j(t) = \frac{M(t)}{2R}$$

$$E = \frac{1}{2}\mu_0 R \frac{dM}{dt}$$



$E \sim e^{j}$ in accordance with ln t decay of M

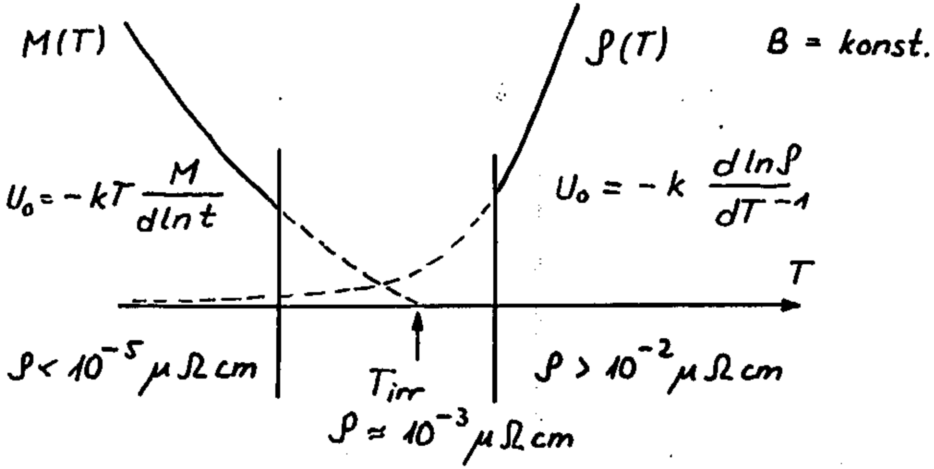
$10^{-1}\,\mu V/cm \geq E \geq 10^{-6}\,\mu V/cm$

$10^{-5}\,\mu\Omega\, cm \geq \rho \geq 10^{-11}\,\mu\Omega\, cm$

comparison between U_0 from <u>magnetic relaxation</u> and <u>resistive transition</u>

Palstra et al.

$$\rho(B,T) = \rho_0 \, e^{-U_0/kT}$$

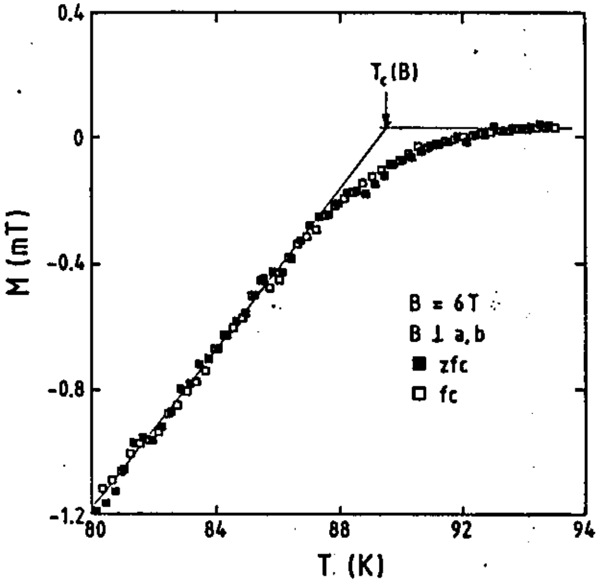


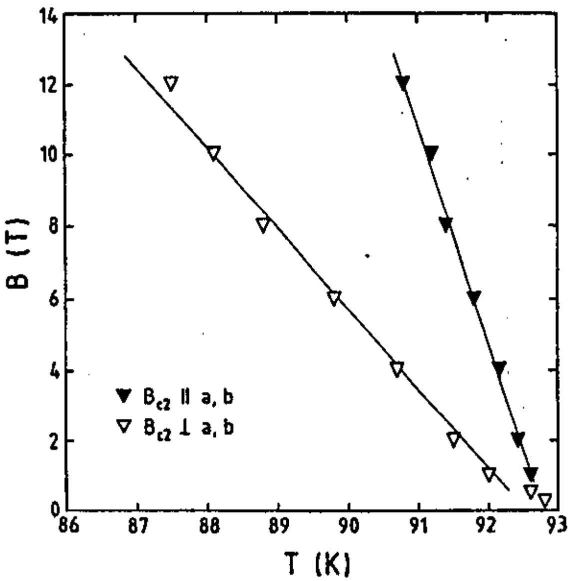
	$M(t)$	$\rho(T)$
B	$< B_{irr}$	$> B_{irr}$
j	$> 10^2\ A/cm^2$	$< 1\ A/cm^2$
E	$< 10^{-3}\ \mu V/cm$	$> 10^{-1}\ \mu V/cm$
$E(j)$	$\sim e^j$	$\sim j$
ρ	$< 10^{-5}\ \mu\Omega cm$	$> 10^{-2}\ \mu\Omega cm$
U_0	$< 0.4\ eV$	$> 1 eV$

?

$B_{c2}(T)$ from reversible magnetization

Finnemore
Welp et al.

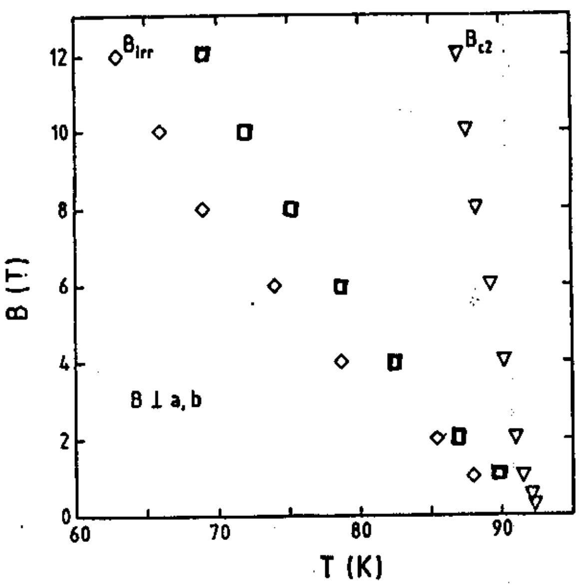




	$B \parallel a,b$	$B \parallel c$
$\frac{dM}{dT}$ (mT/K)	0.031	0.122
$\frac{dB_{c2}}{dT}$ (T/K)	−6.1	−2.4
$B_{c2}(0)$ (T)	388	152
$\xi(0)$ (nm)	0.57	1.44
$B_{c1}(0)$ (mT)	13	41
$\varkappa$	293	92

… dependence of the defect structure

$B_{irr}(T)$. from magn. or ac measurement



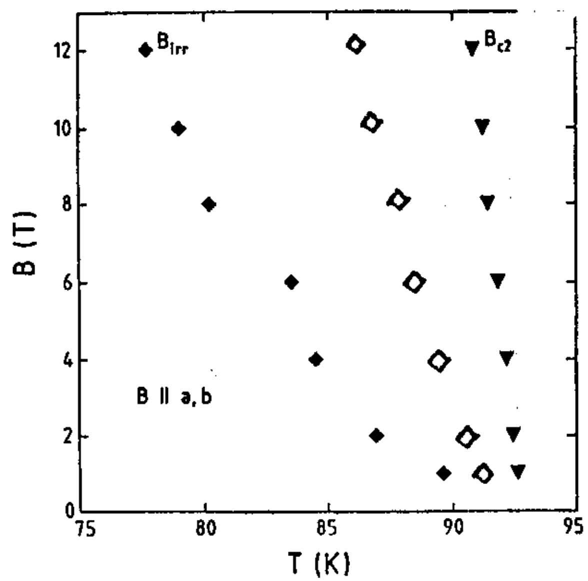
criterion for $B_{irr}(T)$:

$E \approx 1 \mu V/cm$

$\rho \approx 10^{-3} \mu\Omega\, cm$

decreasing sensitivity shifts $B_{irr}(T)$ to higher values :

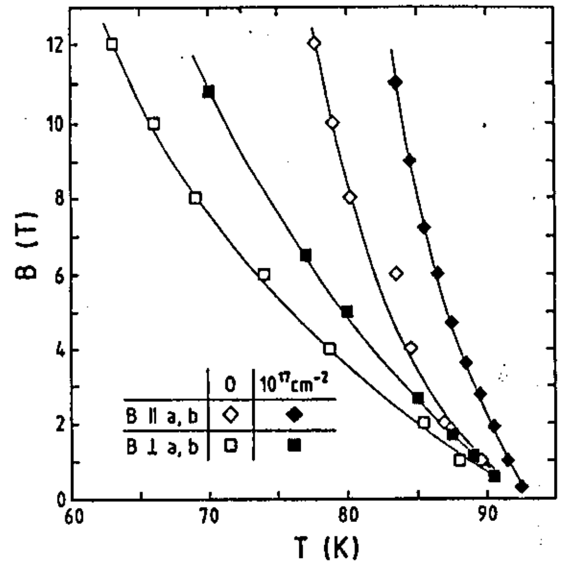
$E \approx 10 \mu V/cm$



T = 77 K
$B \perp a,b$

$B_{c2} \approx 38\,T$

$B_{irr} \approx 4 \div 8\,T$



$B_{irr}(T) = \beta\,(1 - T/T_c)^n$

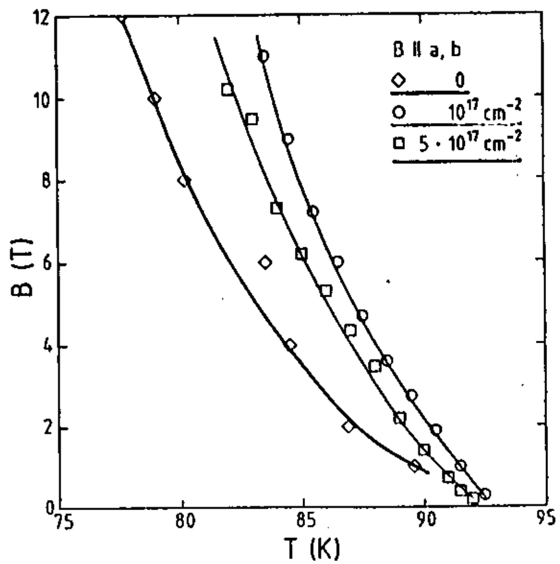
Yeshurun a. Malozemoff

$B \perp a,b \quad n \approx 1.3$

$\beta\,(\phi t = 0) \approx 51\,T$

$\beta\,(10^{17}) \approx 66\,T$

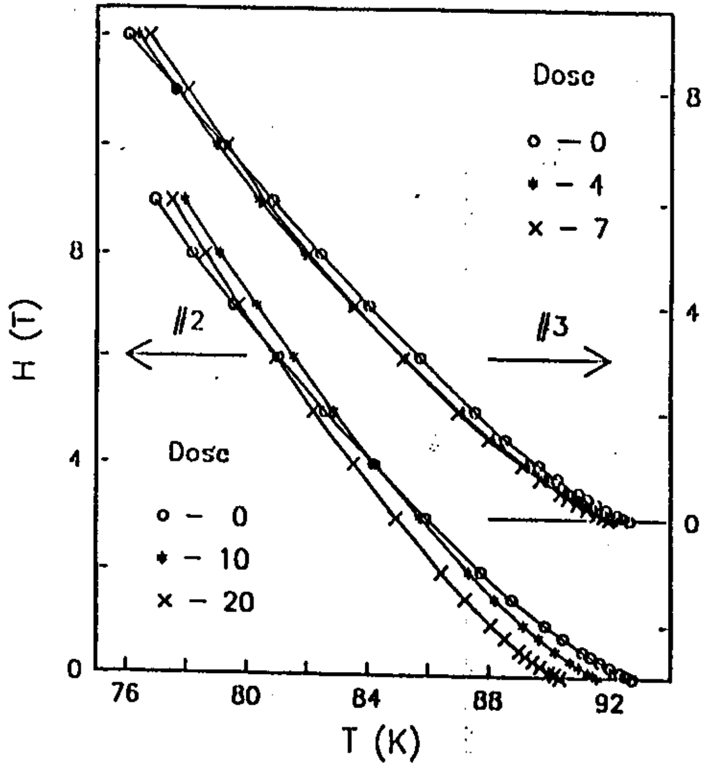
minor increase of B_{irr} inspite large increase of j_c



- flux melting at about $B_{irr}(T)$
- pinning before and after irr. caused by weak el. forces

in agreement with force - displacement curves

A. M. Campbell



Civale et al.

$\frac{j_c}{j_{co}} \approx 100$

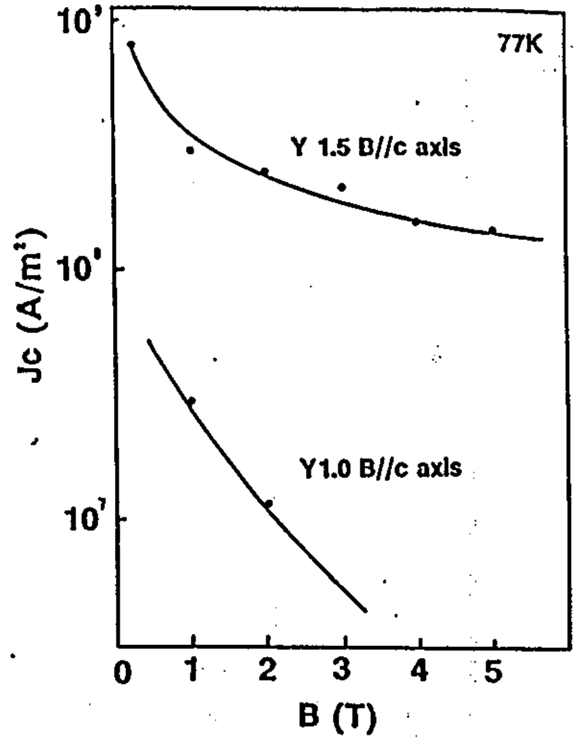
at 77K, 1T

but

no increase

of B_{irr}

Murakami et al.



MPMG $YBa_2Cu_3O_7$

with different

content and size

of 211 inclusions

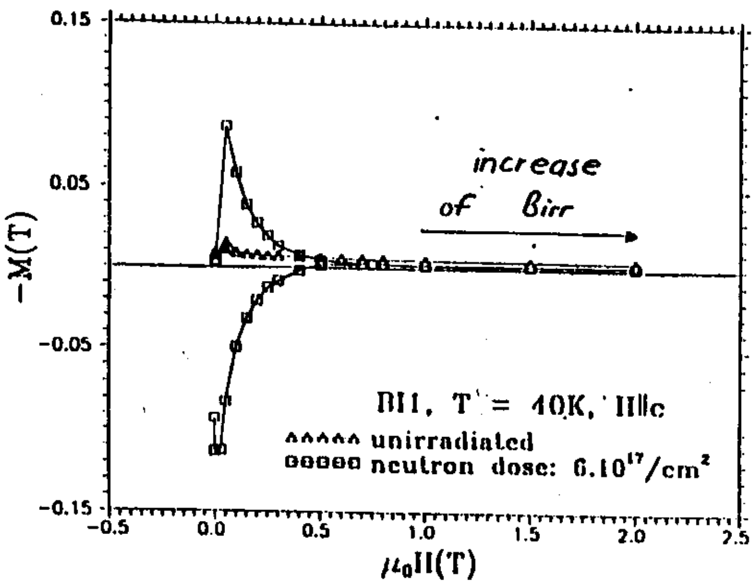
"strong pinning cent...

Y 1.5 25%

1 μm

B_{irr} (77K) ≈ 107

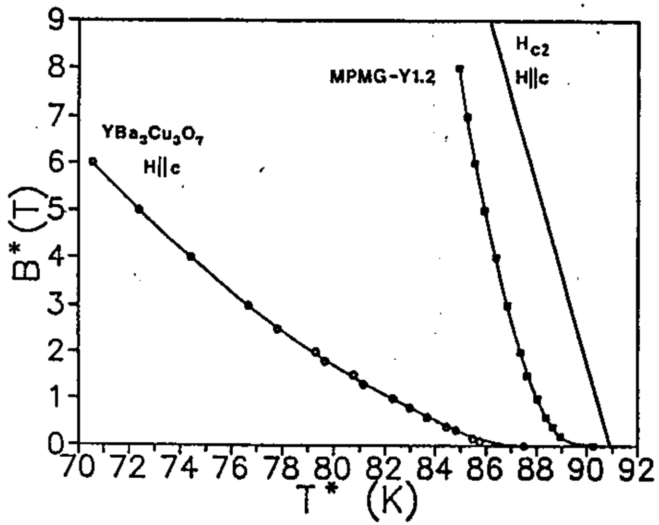
increase of U_0



$Bi_2Sr_2CaCu_2O$

single crystal

Weber et al.



Sagdahl et al